Performance Analysis of Advanced Solar Still Integrated with Heating Coil and Nano Phase Change Material

A Thesis Submitted

In partial fulfilment for the award of the degree of

Master of Technology
In
Thermal Engineering

SUBMITTED BY

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<u>CANDIDATE'S DECLARATION</u>

I, Anil Kumar, Roll No. 2K21/THE/23, hereby certify that the work which is being presented in this thesis entitled "**Performance Analysis of Advanced Solar Still Integrated with Heating Coil and Nano Phase Change Material"** being submitted by me is an authentic record of my own work carried out under the supervision and guidance of **Dr. Anil Kumar, Associate Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.**

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech. Degree.

Place: Delhi
Date: 02/05/2023

ANIL KUMAR
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CERTIFICATE

I, hereby certify that the work which is being presented in this thesis entitled "**Performance Analysis of Advanced Solar Still Integrated with Heating Coil and Nano Phase Change Material** " in the partial fulfilment of requirement for the award of degree of **Masters of Technology in Thermal Engineering** submitted in the **Department of Mechanical Engineering**, **Delhi Technological University**, **Delhi-110 042 (India)**, is an authentic record of work carried out by **Mr. Anil Kumar, Roll No. 2K21/THE/23**, under my supervision and guidance.

To the best of my knowledge, the work presented in this thesis has not been submitted in any other University/Institute for the award of M. Tech. Degree.

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Finally, and most importantly, I would like to thank my family for their help, encouragement and prayers throughout all these months. I dedicate my work to them.

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Abstract

The increasing growth of industrialization and population has led to a global shortage of drinkable water, which has motivated researchers to find an alternate approach to supply this need. Solar stills (SSs) are solar-powered systems that can produce drinking water, although they have a low output problem. In present research work, two different types of SS- a conventional SS and an advanced SS have been studied. To enhance the yield (productivity) of advanced solar stills, an external condenser (EC), water heating coil, and Nano-phase change material (ZnO-PCM) have been used. Performance of conventional SS and advanced SS were compared in three different sets of investigation under the same climatological conditions. The maximum thermal efficiency and improved yield are obtained as 46% & 77%, 53% &119%, and 51% & 113% for ASS (heating coil), ASS-EC, and ASS-ZnO-PCM respectively. Thus, the productivity of ASS (heating coil) was enhanced by around 36% and 42% using ZnO-PCM and an EC, respectively. A study of economic analysis was conducted as well and observed that the desalinated freshwater's acquired prices were 0.030, 0.023, and 0.021 $/l for CSS, ASS-ZnO-PCM, and ASS-EC, correspondingly.

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Nomenclature

SS	Solar still
EC	External condenser
h_{fg}	latent heat of vaporization,
P_F	DC fan power
m_{np}	Mass of nanoparticles (gm)
PCM	Phase change material
η_d	daily thermal efficiency
m	hourly distillate
A	area of the system (m^2)
i	interest per annum (assumed 12%),
n	no. of life in years
I	average solar intensity
CSS	Conventional solar still
m_w	Mass of water (ml)
HC	Heating coil
S	salvage value of the system after n years
ASS	Advanced solar still
L_a	appliances losses
L_t	transmission losses
T_w	Temperature of water (°C)

CHAPTER-1
INTRODUCTION

1.1 Introduction

Solar distillation using solar stills is a process that harnesses solar energy to obtain potable water through a closed natural hydrological cycle. That's why the government needs to pay more attention to this. The use of solar energy for desalination purposes is increasing day by day. This can be the best option to overcome water scarcity to a great extent. Any living thing on earth is possible because of water, be it plants, animals or humans. Human beings are in dire need of potable water for the functioning of body cells. Lack of water in the human body can lead to dehydration. The availability of water on earth is very high, but it is very less in terms of potable water. About 67% of the Earth's surface is covered by water but 97% of the total water availability is in the ocean, and lakes, which are not pure water and have 35000 to 45000 ppm and lots of impurities and are not suitable for use in day to day activities. According to the World Health Organization (WHO), only water with a salinity of 1000 ppm can be consumed by the human body. The glaciers contain over 2% of pure water, and 0.97% is potable. Fig 1.1 shows the existence of water spaces on the surface of the Earth. According to the United Nations (UN), more than two billion people face the problem of access to drinking water [1]. By 2025, 67% of the world's population will face a shortage of potable water and there will be a huge demand for portable water. The world's population is growing rapidly, therefore, water resources have to be developed accordingly. Also, an increase in population coupled with factors such as urbanization and industrialization will increase the demand for potable water. If the demand for potable water is not met, it will have negative effects on human health and the environment [2]. There are many methods available to purify water, but solar distillation is an eco-friendly, low-cost, renewable and easy-to-operate technology to purify water.

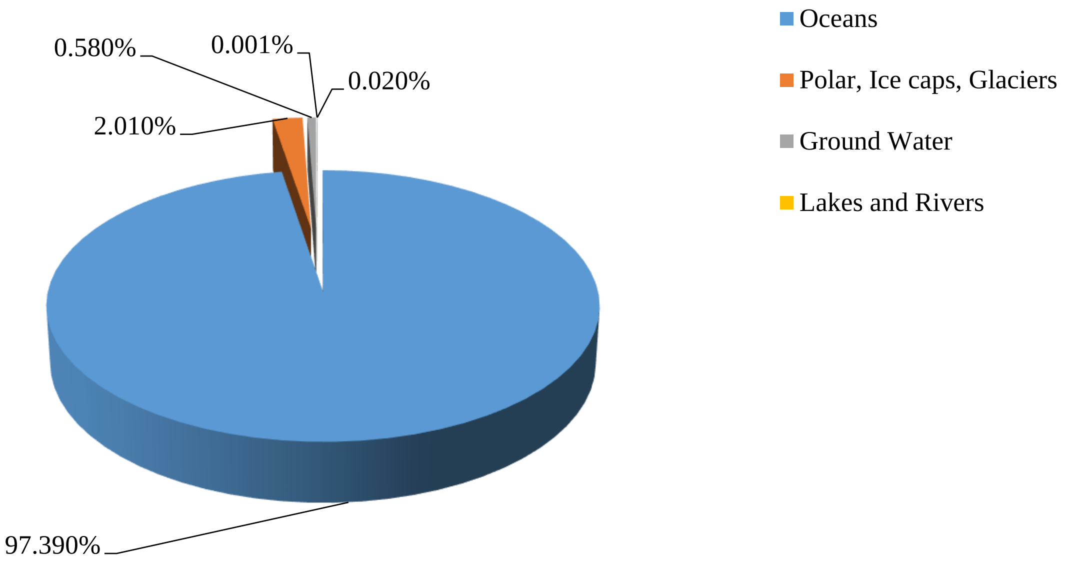


Figure 1.1 Water availability on earth's surface [1]

1.2 What is distillation?

Distillation is the process of purifying a liquid by condensation and boiling, to separate substances. When thermal energy is applied to liquid/water, it vaporizes. Later the vapor condenses to form distillate. The process of open-cycle distillation is shown in Fig. 1.2.

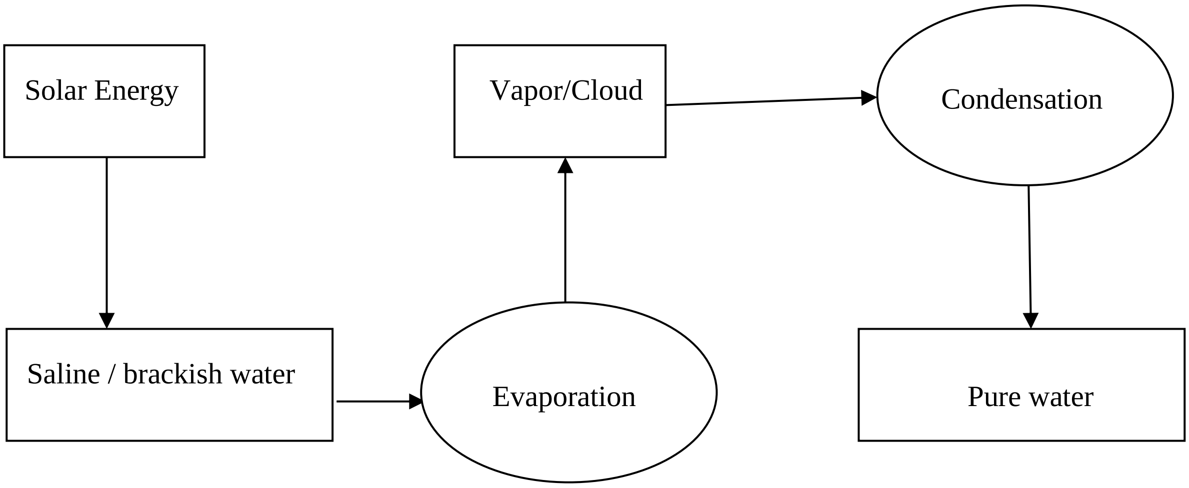


Figure 1.2 Layout of opened cycle distillation

1.2.1 Solar distillation

The distillation process is caused by solar radiation which is called solar distillation. It is a natural process with the help of solar energy in close cycle. Furthermore, solar distillation can be classified as;

(i) Passive solar distillation process (ii) Active solar distillation process

In the passive solar distillation process, brackish water is feed into the basin without the help of external sources, while in the active solar distillation process, a secondary source is provided to feed the water. This extra heat energy increases the evaporation rate. The secondary sources of heat rise include collectors, concentrators, etc., which are further classified as single and double slope solar distiller units based on structure and position. To get the maximum amount of solar energy, the orientation of the single slope is towards south and the double slope is towards east-west. Fig. 1.3 represents the full classification of solar distillation system. Furthermore, passive solar stills can be divided into symmetric and asymmetric types. Glass cover tilt matters in a symmetric or asymmetric distiller unit. Active solar distiller units can be divided into two types high temperature and nocturnal distillation. High temperature distiller can be divided into auxiliary and heating two parts by collectors. The heating is further divided into three parts by the collectors which are Flat Plate Collector (FPC), Compound Parabolic Concentrator (CPC), and Evacuated Tube Collector (ETC).

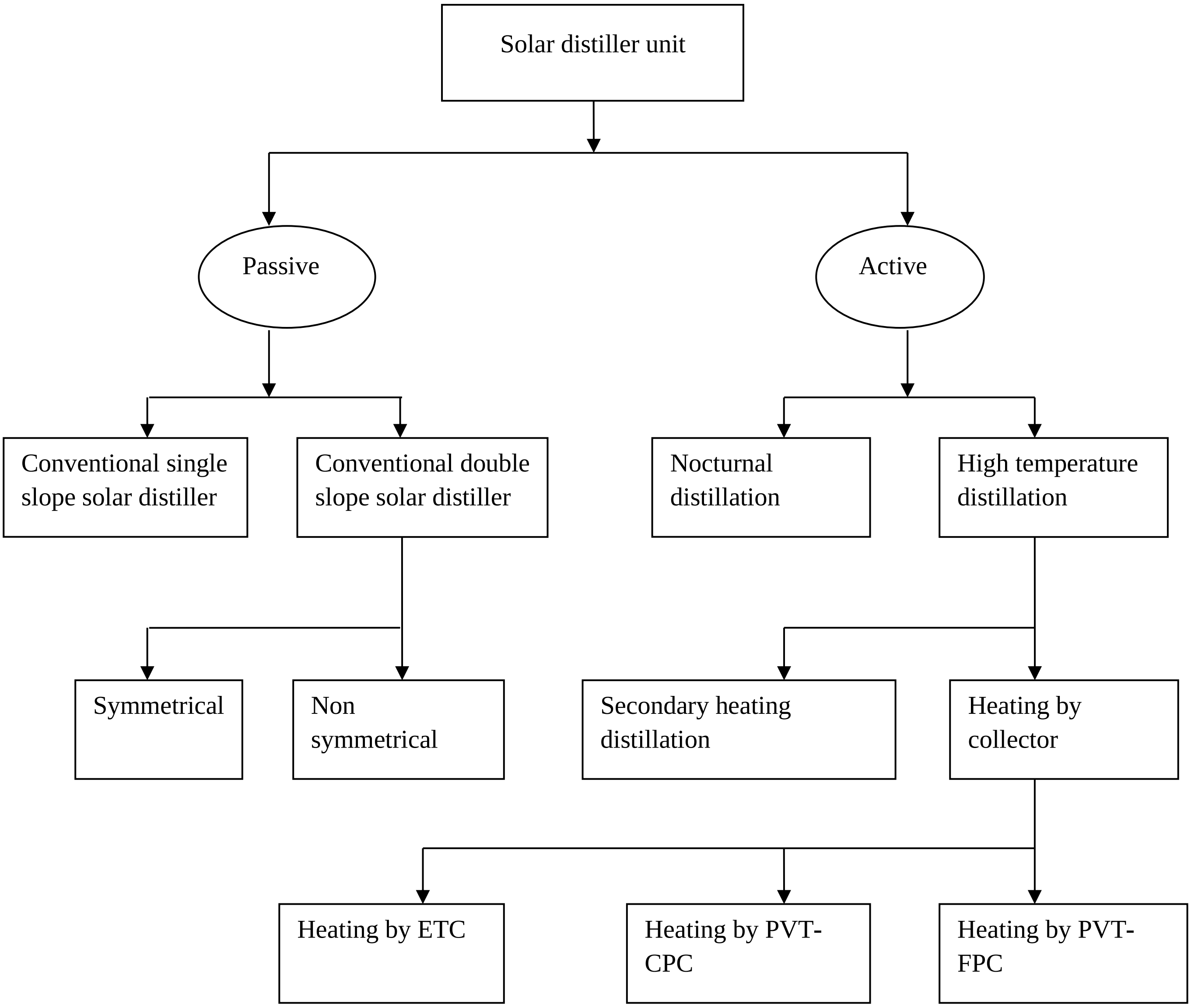


Figure 1.3 Classification of solar distillation system

To develop self-sustainable systems, flat plate collector (FPC) is used with fully or partially covered surface. Later on, the flat plate collector can be connected to a compound parabolic concentrator, while the flat plate of the photovoltaic (PVT) is used alone for power generation by converting thermal into electrical energy. This electrical energy is mainly used for running the pump and rest for other works. Recent researches focus on active solar distillers single and double slope, consisting of N-incorporating photovoltaic compound parabolic concentrator collectors (N-PVT-CPCs) with helically coiled heat exchanger.

1.3 Construction material of solar still

The construction of solar distiller is very simple even local materials can be used for construction. However, good quality ingredients will increase the cost of the distiller. The materials used must be strong against wind and minor earthquakes. It should not be toxic, encourage different flavors as the temperature rises and vapors are released.

It should be compact to be easily carried by local transport and should have corrosion resistance to saline water. Film-wise condensation should occur on the glass cover because drop-wise condensation reduces the intensity of solar radiant energy. The following materials can be used for manufacturing the solar distiller unit: Fiber Reinforced Plastics, Galvanised Iron. Top cover materials such as sheet, concrete and glass and plastic.

1.4 Mode of heat transfer

The heat transfer modes in active single and double slope solar distillers, incorporating photovoltaic thermal are conduction, convection, radiation and evaporation, which can be further classified as internal and external heat transfer.

1.4.1 Internal heat transfer mode

Radiation, evaporation, and convection all contribute to the heat transmission from the condensing cover to the water surface inside the solar distiller.

1.4.2 External heat transfer mode

Convection and radiation from the top are the methods used in solar distillers to transmit external heat. Conduction and convection are the methods used in the environment to move heat from the sides and the bottom.

1.5 Basic concept of solar distillation

The fundamental idea behind water condensation and vaporization is the greenhouse effect. Solar radiation serves as the thermal energy source in solar distillers, which are used to produce potable water. The design for a typical single slope active solar distiller is shown in Figure 2.1. The box's components include fiber reinforced plastic (FRP), G.I. sheet, wood/concrete, and insulated coatings that absorb heat from the bottom wall and sides. Condensed water drips down from the glass lid that closes the top of the box. The condensed water descends to the inner surface due to gravity and is gathered in a jar. The box's lower surface, which has been darkened, absorbs almost all of the radiation that hits it. Basin liner is the term used to describe this darkened bottom area.

A sizable percentage of the solar radiation that strikes the glass cover after transmittance is absorbed by the water in the basin. The tiny amount of radiant energy that is approaching the water's surface returns and the remainder is primarily absorbed by the blackened surface. Absorptivity and profundity play a role in how much solar radiation is absorbed by the water, which raises the temperature of the basin lining. Most of the heat is later transferred to water mass by convection, and very little is lost to the atmosphere by conduction. As a result, the temperature differential between the surfaces of the glass and the water grows. By releasing latent heat, the water mass evaporates and experiences film-wise condensation on the inner surface of the glass. Condensed water drips into a container and then emerges for additional use.

The distillate obtained is not suitable for direct drinking, but it will be suitable for drinking and cooking after adding minerals. The daily production from a single slope passive distiller unit varies from 0.5 l/m^2 to 2.5 l/m^2 from a single slope solar distiller. Thermal efficiency from 5 to 40% in one year. The merits of solar distiller units over other distiller technologies are as follows.

- The passive sun distiller has no moving parts.
- It is a simple and affordable method of supplying drinkable water.

- It is sustainable and has low environmental impact when in use.
- It can be operated by unskilled or semi-skilled labour.
- Locally produced and repaired.
- This system is very helpful in regions with brackish or salty water.
- The importance of self-sustainability is increasing, and photovoltaic thermal modules can produce enough extra energy to meet demand.
- It is a more convenient and easy-to-use unit than a water treatment facility.

Additionally, a system has advantages and disadvantages that restrict the use of technology for mass production. The following factors are present: (a) weather-dependent unit; (b) large solar collection area required for commercial purposes; (c) low performance; (d) higher initial investment; (e) requirement for continuous feeding and flashing; and (g) requirement for robust system for open system.

1.6 Applications of distillate

There is no cost and no need to spend anything on solar energy. However, the expense of distilled water and the need for a large space are caused by the investment in the fabrication of the distiller unit. Large-scale production is therefore not economically feasible for uses such as domestic supply, commercial use, agriculture, etc. As a result, it is only applied to the domestic water purification process as well as some laboratory and greenhouse uses. The water that has been solar-distilled can be used for drinking, bathing, cleaning, cooking, lab work for analysis, and medical sterilization. Additionally, it can be used to maintain phone communication in batteries. Additionally, it has a variety of uses in business and agriculture. Although it has a poor economy, it can be used to reclaim salt.

Potable water may be recovered from effluent, but some odorous gases may evaporate, condense, and combine with distillate. Alcohol production may also be a factor in sun distillation.

CHAPTER-II
LITERATURE REVIEW

2.1 Introduction

The power of sun is a more important source of renewable energy and plays a significant role in solar water heating, solar cooking, solar drying [3], [4], air heating, solar cooling, power generation, and water desalination. Among the earlier solar energy methods, solar water desalination is an efficient and attractive technique for providing drinkable water, which is the life of all living being [5]. Several techniques of solar water desalination have been studied and put for experiments. Amongst them, solar stills (SS) are more common, lower price, small scale, and existing system which can be used to stock drinkable water for human begin in arid regions. A number of studies have been carried out to improve the productivity as well as thermal efficiency of SS systems[6], [7]. Numerous solar still system geometries, such as stepped solar still [8], [9], half barrel solar still [10], pyramid solar still [11], [12], conventional solar still [13], trays solar still [14], single slope solar still [15], double slope solar still [16], and tubular solar still [17] have been put to the test in a variety of design and operating scenarios. In addition, the performance of solar still systems has been improved by the introduction of reflectors [18], nanoparticles [13], phase change material [19], wick material [20], fins [21], and spinning components [9]. Andre et al. developed a thermal model to optimize and forecast the thermal analysis of solar still. The schematic view of the experimental setup is demonstrated in Fig 2.1. This developed model tested actual ideas for improving the SS performance and took into account the impact of walls and shadowing. The findings demonstrated that when water depth and wall height were reduced and insulation levels were increased, and reflectors were added, conventional solar still performed significantly better [22].

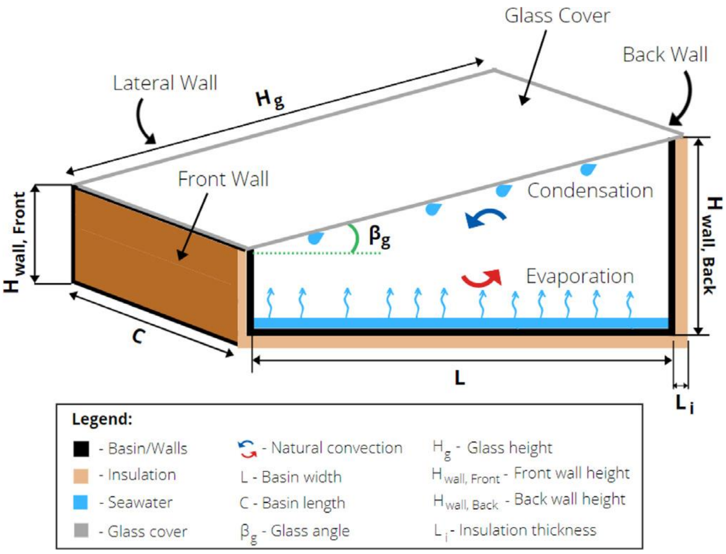


Figure 2.1 Schematic view of experimental setup

Dumka et al. improved the conventional solar still (CSS) by employing 100 cotton sacks packed with sand at different water depths. The outcomes of this research indicated that CSS has more productivity (31%) using sandbags compare to general CSS [23]. Dumka et al. also evaluated the theoretical as well as practical study on CSS using fixed ring magnets. The results demonstrated that CSS has more productivity (49%) using permanent magnets compared to CSS. The actual snapshot of the experimental setup is shown in Fig 2.2 [24].

Figure 2.2 Actual picture of developed experimental setup

Panchal et al. evaluated the thermal performance of CSS using a mixture of carbon powder and black paint at various concentrations. As the concentration of carbon powder varied in the range of 20-40%, the productivity also improved in the range of 10.5-17%. Due to this concept, water temperature increases, and the heat transfer rate also increased [25]. Panchal et al. developed an advanced single slope solar still coupled with ETSC and small calcium stones also used [26]. The experimentation procedure was categorized into two cases: In Case-I solar still assisted with ETSC and Case-II solar still coupled with ETSC using calcium stones. The findings indicated that the productivity of SS increases by 114% and 105% in both cases respectively. Also, SS yield improved by 20% by using a rock stone bed which acts as an energy-storing device. Murugavel and Srithar fabricated a novel double slope basin type SS using different wick materials as well as aluminium fins (shown in Fig 2.3). It was observed that a large quantity of mass distillate was produced using light black cotton cloth [27].

Figure 2.3 Demonstration of different wick materials.

Agrawal and Singh designed and developed a double slope basin-type solar still using copper tubes and copper cylinders filled with PCM. Therefore, the yield of solar stills has been tested at different salinity levels. Alawee et al. investigated a double-slope solar still with an elevated basin [28]. Multiple approaches are used to make a profit from solar intensity that hits the back wall of solar still. Younes et al. evaluated the performance analysis of corrugated absorbers as well as half-barrel absorber solar still using wick material on the side walls of SS [29]. The purpose of wick material is to enhance surface area where water evaporates and protects side walls of solar still from direct beam radiation. Due to this, rate of evaporation and condensation improved whereas rate of heat losses decreased. It was noted that corrugated SS and half-barrel SS had per day yield 139% and 154% respectively compare to CSS [8]. Essa et al. developed a new system, in which a rotating disc fitted on back side wall of CSS (revealed in Fig 2.4). The whole experimentation work was carried out in two phase. In Phase-I the rotating disc is used while in phase-II the rotating disc is used with wick material. Results demonstrated that corrugated disc SS with wick material produced 124% more drinkable water [29].

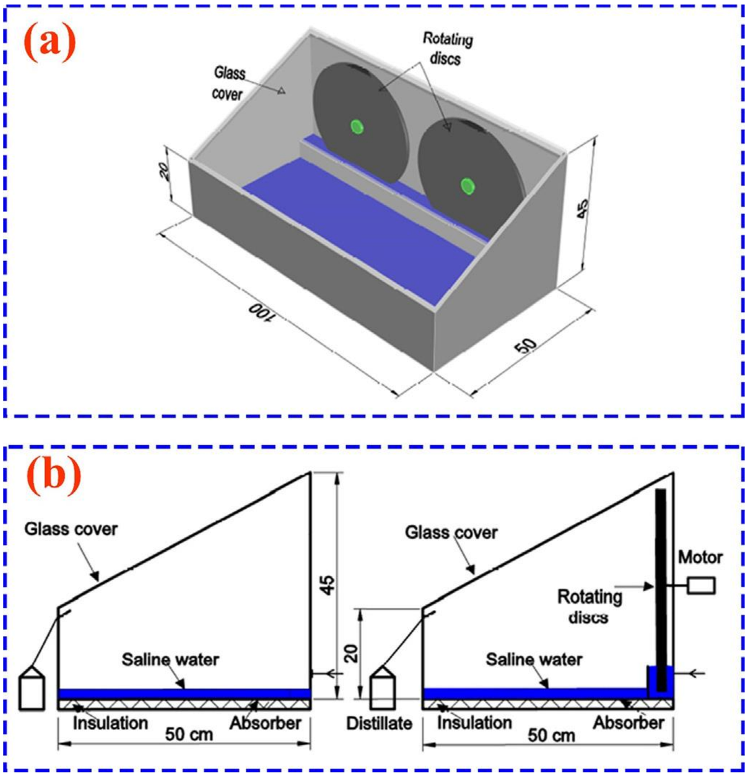


Figure 2.4 Demonstration of experimental setup

Younes et al. evaluate the effect of 04 rotating discs on the side and back wall of SS. It was noted that finned shape disc give better results with SS compared to corrugated and flat type discs (presented in Fig 2.5). The yield enhancement over CSS for finned type, flat type, and corrugated type disc SS was 106%, 68%, and 86% respectively [30].

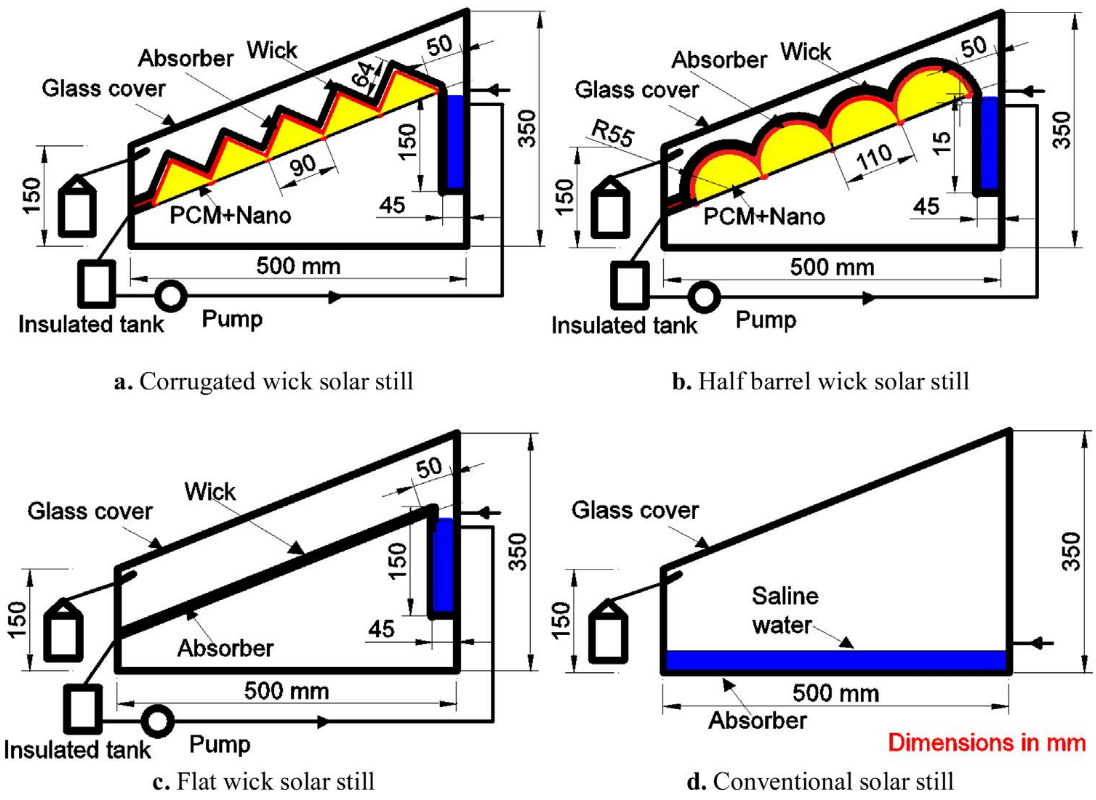


Figure 2.5 Schematic view of experimental setup

Abdullah et al. modified the CSS by implementing the internal trays on rear side wall. It was observed that 95% more drinkable water was produced in trays SS using internal and external reflectors compared to CSS. Also, the yield of SS can be achieved 108% more than CSS by increasing the trays [31].

CHAPTER-III
PROBLEM STATEMENT

3.1 Research Gap

A comprehensive review of previous research discloses that several attempts have been made for the improvement of solar intensity striking with the back wall of SS. To fulfill these criteria a number of auxiliary devices such as rotating discs, vertical wicks, and trays were used. No study has been carried out on the heating as well as condensation on rear wall surface. To conduct the condensation process on its surface and raise the feed water's temperature in this experiment, cold feed water is delivered through a copper coil mounted to the back wall. The back side wall's temperature drops once the copper coil heater is installed, minimizing the amount of heat that is lost to the surrounding air. Furthermore, the impact of using a Phase Change Material (PCM) bed combined with nanoparticles (ZnO) or an external condenser with an electric fan has been considered.

3.2 Research Objectives

i. To evaluate the thermal performance analysis of conventional solar still (CSS) and advanced solar still (ASS) integrated with nanophase change material (ZnO-PCM).
ii. To investigate the productivity and accumulated productivity.
iii. To carry out the Environmental analysis of CSS and ASS.
iv. To evaluate the Economic analysis of CSS and ASS.
v. To study the impact of an external condenser with an electric fan has been considered.

CHAPTER-IV
METHODOLOGY

4.1 Introduction

The research methodology adopted to achieve the objective of the present research work involves a systematic approach of adopting a three-stage appropriate method: -

- Preparation of Nanofluid and measurement of physical properties of nanoparticles in synthesis lab of Madhav Institute of Technology Science, Gwalior (M.P).
- An experimental analysis was done on the designed setup.
- The analytical calculation was done through mathematical relations.

4.2. Material and Methods

The fabrication, installation, and procedure for the experiment are discussed in this section.

4.2.1 Material used

A stainless steel sheet of 2mm thickness (thermal conductivity 58W/m^{2}K, & density 7.80 g/cm^3), plywood of thickness 20mm, and thermocol (polystyrene) of thickness 20mm were brought from local market of Gwalior, M. P (India). A toughened glass of 4mm thickness was used to enclose the system. Copper tube of 5mm diameter was used to make a condenser on the back walls of solar still.

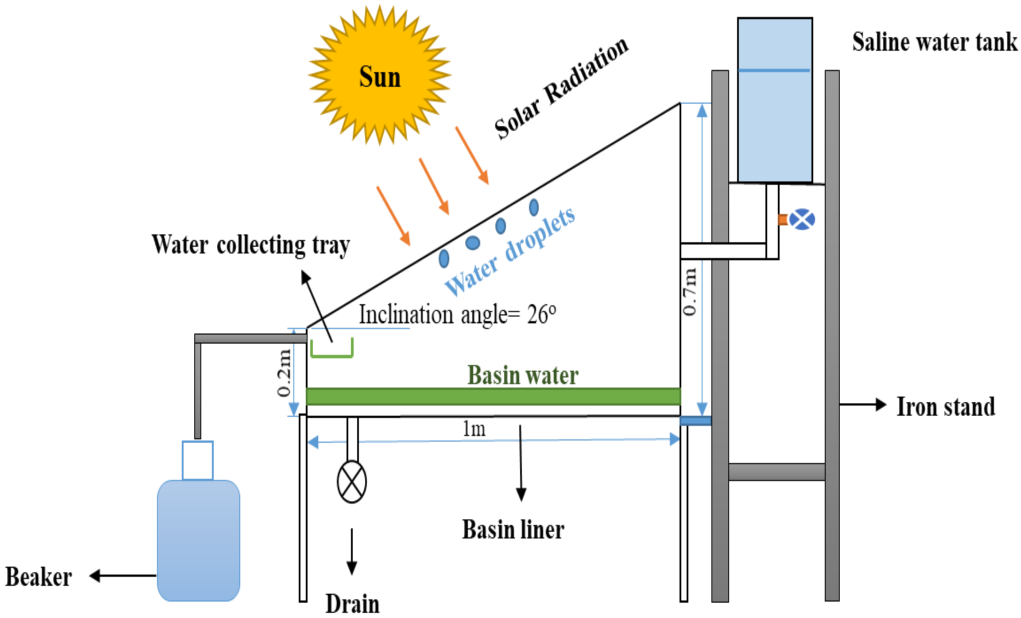
4.3 Methodology

In the current research, two different types of SS systems have been fabricated in solar energy lab of Madhav Institute of Science & Technology, Gwalior India. The first one is considered as a CSS, while the second SS is advanced (ASS) as shown in Figures 4.2 (a) and 4.2 (b) respectively. A stainless steel sheet of 2mm thickness was used to build the CSS. A detailed description of CSS and ASS was discussed in Table 4.1. A toughened glass of 4mm thickness was used to enclose the system and act as a condensing surface. The lower edge of the SS has been welded with an angled trough that will capture the condensate and transmit it to a calibrated beaker. The ASS was also designed in the same manner as CSS with some modifications. The modification that was emendating in ASS was classified into three categories. In Category-I, the copper tube heater (5m length and 5mm diameter) was used. The copper coil also serves as a condenser because cold water enters into it, which causes some steam to condense. Underneath the copper coil on the back wall of solar still, there is an inclined trough where the condensate is collected. In Category-II, to increase the SS yield, a DC fan of 6 watts and 100mm diameter was attached to the rear wall of SS to extract steam to an external condenser and improve condensation method. In Category-III, a 20mm PCM-ZnO layer was considered beneath of absorber plate. The black paint was painted inside and outside of SS system to improve the absorptivity of solar intensity. The main motive of this study is to put a copper tube heater on back wall of the CSS in order to heat feed water before it reaches the SS. Installing the copper tube heater also decreases the temperature of the back wall, reducing the amount of heat lost to the surrounding air. Due to increased evaporation and condensation caused by using copper heating coil, temperature of the glass covers increased. To reduce glass temperature and boost production, two strategies were used. The first approach involved extracting steam from the distiller and condensing it inside the feeding tank. Condensation occurs and raises the temperature of feed water. Therefore, using a fan can help decrease the glass cover temperature. The second approach was to use a 20mm PCM-ZnO nanoparticle's layer beneath of absorber plate to enhance the thermophysical properties of working fluid.

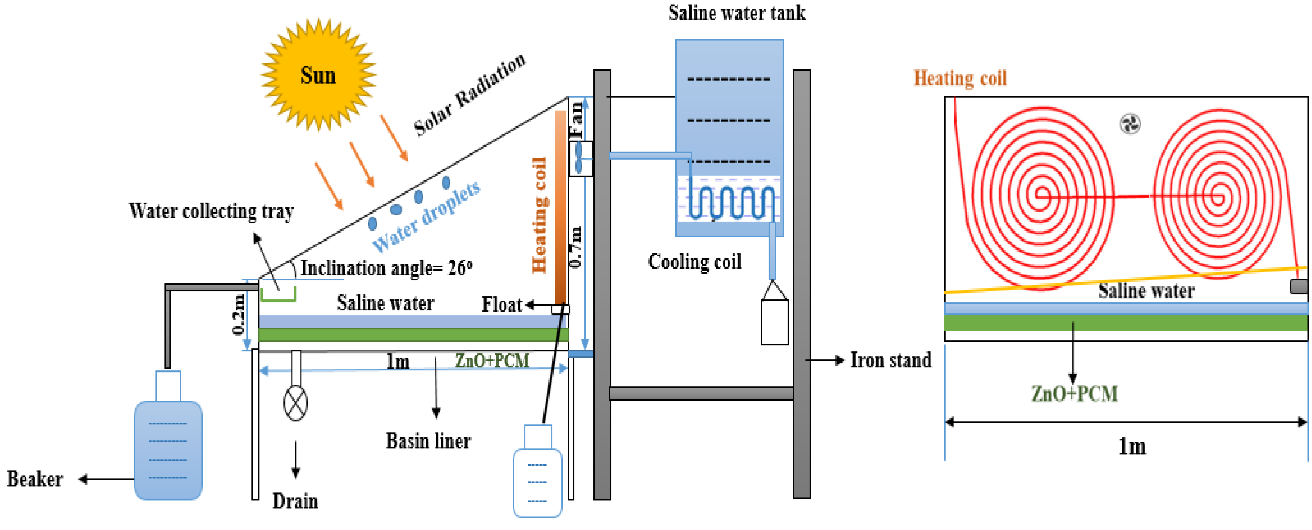
Table 4.1 Detailed description of experimental setup

Component	Description
Solar still	
Plywood	Thickness of 20mm
Thermocol	Thickness of 20mm
Steel sheet	Thickness of 2mm
Glass cover	Thickness on 4mm
Iron stand	02 (thickness on 5mm)
Basin area	1m × 1m
Lower height	0.2m
Height of back wall	0.7m
Inclination angle	26^{o}
Latitude of site location	26.2183° N, 78.1828° E
DC fan	
Types	06 W DC solar powered
Copper tube	
Length of copper tube heater	5m
Diameter of copper tube	5mm
Thickness of PCM-ZnO layer	20mm

Figure 4.1 Photographic view of experimental setup



(a) Conventional Solar Still (CSS)



(b) Advanced Solar Still (ASS)

Figure 4.2 Schematic view of experimental setup

4.4 Instrumentation for environment data recording

i. Data-logger (Data Taker DT85 series 3, Australia) was installed and recorded relative humidity (Rh) and ambient air temperature. Experimentation work was carried out from 1000 hrs to 1800 hrs.

ii. An anemometer (Dynalab DLAW 8701) was used to measure the airflow rate (m/s) over the glass cover of CSS and ASS.

iii. Solarimeter (Megger PVM 210) was mounted and used to record direct beam radiations as well as diffused solar radiations at an interval of time.

iv. K-type thermocouples were used to record the temperature at different locations of SS (CSS and ASS).

4.5 Calculation of uncertainty

The instruments used for measuring various parameters along with their accuracy, range, standard uncertainty are shown in Table 4.2. The uncertainty in various observed parametrs were determined using experimental data (y) are depicted in Table 4.2. Standard uncertainty of instruments used was calculated using Eq.1.

$$\text{Standard Uncertainty} = \frac{\text{Accuracy of instrument}}{\sqrt{3}} \qquad (1)$$

If $X_1, X_2 \ldots\ldots X_n$ are the independent variables affecting the observed parameter Y, then the uncertainty in observed variable $U(Y)$, was computed using Eq. 2 [32]:

$$U(Y) = \left[\left(\frac{\partial Y}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial Y}{\partial x_2}\right)^2 u^2(x_2) + \cdots \ldots \ldots + \left(\frac{\partial Y}{\partial x_n}\right)^2 u^2(x_n)\right]^{1/2} \qquad (2)$$

Where, $U(Y)$ is the total uncertainty, $u^2(x_1)$, $u^2(x_2)$, ….,$u^2(x_n)$ are uncertainties of independent variables.

Table 4.2 Detailed description of uncertainty of used instruments

Instruments	**Observed parameters**	**Accuracy**	**Ranges**	**Standard uncertainty (σ)**	**Uncertainty of observed parameters**
K-types thermocouple (PT-100 and PT-1000 sensor)	Temepaerature at various point	±0.1℃	-140 to 990℃	0.0578℃	±0.265℃
Infrared Temperature gun (HTC, MTX-2)	Temeperature of glass cover and side walls	±1℃	-40 - 500℃	0.58℃	±1.175℃
Solarimeter (PMV-210)	Solar radiation	±10 W/m^2	0-2000W/m^2	5.77 W/m^2	±5.77 W/m^2

DYNALAB DLAW-8701 Digital Anemometer	Velocity of air	±1m/s	0-45m/s	0.58 m/s	±0.64 m/s
MEXTECH TM-1 Digital Hygrometer	Humidty	±2%	5-85%	1.15%	±1.29%
Graded bottles	Yield	±0.2l	0.01l	0.121	±0.2l

4.6 Nanofluid preparation

Nanoparticles are hydrophobic in nature, to make nanoparticles hydrophilic some mythologies have been implemented. Figure 4.3 demonstrate the step involved in the preparation of nanofluids. Usually, it was observed that most of the researchers have adopted surfactants and dispersants to make nanoparticles solvable in water.

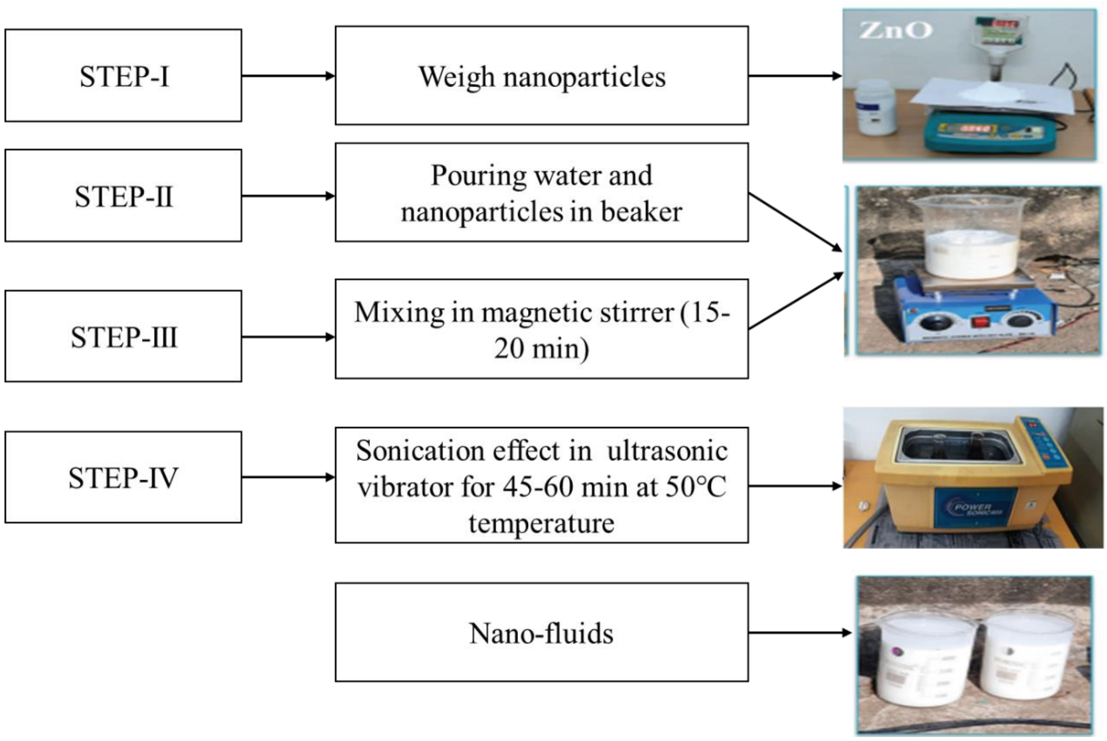


Figure 4.3 Layout diagram of nanofluids preparation

The boiling point temperature of water increases due to surfactants and dispersants, by virtue of which water will evaporate slowly. The detailed specification of ZnO nanoparticles is given Table 4.3. The concentration of nanoparticles is determined using Eq. 14 [15].

$$\varphi_{np} = \left({m_{np}}/{m_{np} + m_w} \right) \times 100 \qquad (14)$$

Table 4.3 Specification of ZnO nanoparticle

Nanoparticles	**Thermal conductivity (W/mK)**	**Density (kg/m^3)**	**Size of particle (nm)**	**Appearance**	**Specific heat (J/kg K)**
ZnO	6.5	6000	30-50	White	443.4

4.7 Thermal efficiency of system

The thermal efficiency of solar still system can be calculated using the following relations[33]:

$$\eta_d = \frac{\sum m^{\cdot} \times h_{fg}}{\sum A \times I + P_F} \qquad (3)$$

η_d - Daily thermal efficiency

h_{fg}- Latent heat of vaporization

$m^{\cdot}$ - Distillate per hour

I - Daily average solar radiation

P_F - Power of fan

A - Area

T_w - Water temperature

Latent heat of vaporization according to water temperature can be evaluated as [34]:

$$h_{fg} = 3.1625 \times 10^{6} + [1 - (7.1616 \times 10^{-4} \times T_{w})] \text{ for } T_{w} > 70℃ \quad (4)$$

$$h_{fg} = 2.4935 \times 10^{6}[1 - (9.4779 \times 10^{-4} \times T_{w}) + (1.3131 \times 10^{-7} \times T_{w}^{2}) - (4.7974 \times 10^{-9} \times T_{w}^{3})] \text{for } T_{w} < 70℃ \quad (5)$$

4.8 Economic analysis

The objective of system modification is to lower production costs while also increasing water productivity. Various factors, including setup size and design, insulation and fabrication materials used in SS, site location, labour costs, and feed water quality, raise the cost of producing SSs water [15].

Capital recovery factor (CRF) can be evaluated as:

$$CRF = \frac{i(1+i)^{n}}{[(1+i)^{n}-1]} \quad (6)$$

While, F = current capital cost, therefore the fixed annual cost (FAC) and Annual salvage value (ASV) can be calculated as:

$$FAC = F(CRF) \quad (7)$$

Further, current capital cost (F) can be rewritten as:

$$F = \text{Cost of system} + \text{Cost of Nanoparticles} + \text{Cost of all needed devices} + \text{Labour cost}$$

$$ASV = (SFF)S \quad (8)$$

The value of S =0.2F, SFF= Sinking fund factor and can be determined using Eq. 8

$$SFF = \frac{i}{[(1+i)^{n}-1]} \quad (9)$$

Total yearly expense (TAC) can be computed using following relations:

$$\mathrm{TAC} = \mathrm{FAC} + \mathrm{AMC} - \mathrm{ASV} \qquad (10)$$

Therefore, AMC = Costs of yearly upkeep, which includes the cost of paint, labour cost, sealing material cost, and all breakdowns cost. That measured to be 15% of FAC. It may be written as[15]:

$$\mathrm{AMC} = 0.15\mathrm{FAC} \qquad (11)$$

The cost of distilled water per liter (CPL), can be computed as:

$$\mathrm{CPL} = \frac{\mathrm{TAC}}{\mathrm{M}} = \frac{\text{Total yearly expense}}{\text{Total yearly yield}} \qquad (12)$$

The time consumed by the experimental setup to return the invested cost is known as the payback period. The payback period $(\mathrm{n_p})$ for the advanced system is calculated as:

$$n_p = \frac{ln\left(\frac{M_y \times S_p}{(M_y \times S_p) - (CC \times i)}\right)}{ln(1+i)} \qquad (13)$$

4.9 Environmental analysis

Environmental analysis plays a significant role in showing the impact of advanced solar still (ASS) system on the atmosphere. Solar stills system is the best example of a sustainable system and also does not affect the atmosphere in any manner. First step in environmental analysis is to calculate the embodied energy of both advanced SS and conventional SS. Table 4.4 specifies the amount of embodied energy for different used materials to fabricate both systems. Therefore, the assumption and relations used in the calculation of environmental analysis are discussed in Table 4.5. The calculated value of EBPT, CO_2 Mitigation, Carbon Credit Earned, CO_2 Emitted, and Net CO_2 Mitigation (Lifetime)

Table 4.4 Embodied energy of used material

Materials used	Embodied Energy (kWh/kg)	Mass (kg)	Total Embodied Energy (kWh) CSS	Total Embodied Energy (kWh) ASS
Plywood (for structure)	10.5	10	105	105
Thermocol (for insulation)	89.0	0.25	22.25	22.25
Copper tube	19.85	5	00	99.25
Stainless steel	55.65	12.5	695.25	695.25
Al frame	165	0.25	41.25	41.25
Paint	91.01	0.25	22.75	22.75
Fitting materials(valve and nozzle)	56.12	2.1	117.85	117.85
DC fan made of plastic	19.54	0.4	00	7.816
Oil paint	25.25	2	50.5	50.5
PV panels	740	01 no.	740	740
ZnO nanoparticles	55	0.02	00	1.1
Electricity wire	19.59	0.1	1.959	1.959

Al T and L-shaped joint	55.25	26	1436.5	1436
Glass	15.9	8	127.2	127.2
Total embodied energy			**3360.014**	**3468.18**

Table 4.5 Equations used for calculation [37-38]

Eq. No.	Equations	Ref.
13.	$\text{Energy Payback Period} = \frac{\text{Emboided Energy } (E_e)}{\text{Annual Thermal Energy Output } (E_a)}$	[35]
14.	$CO_2 \text{ emission per year} = \frac{E_e}{L} \times 0.98 \text{ kg}$ $CO_2 \text{ emission per year} = \frac{E_e}{L} \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_t} \times 0.98 \text{ kg}$ If L_t = 0.40 and L_a = 0.20 due to old appliances, then Eq. becomes as follows: $CO_2 \text{ emission per year} = \frac{E_e}{L} \times 2.042 \text{ kg}$	[35]
15.	$CO_2 \text{ mitigation per year} = E_{system} \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_t} \times 0.98 \text{ kg}$ $CO_2 \text{ mitigation per year} = E_{system} \times 2.042 \text{ kg}$	[36]

16. For a life span of N years, it would be [36]

$$= E_{system} \times N \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_t} \times 0.98 \text{ kg}$$

For a life span of N years, it would be $= E_{system} \times N \times 2.042$ kg

17. Net CO_2 mitigation = Lifetime CO_2 mitigation - Lifetime CO_2 emission [35]

$$= (E_{system} \times N - E_e) \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_t} \times 0.98\text{kg}$$

$$= (E_{system} \times N - E_e) \times 2.042\text{kg}$$

The conversion rate of 1 USD in Indian currency is nearly 80 rupees (https://www.exchangerates.org.uk/USD-INR-20_01_2023-exchange-rate-history.html as on 20 Jan 2023).

CHAPTER-V
RESULTS AND DISCUSSION

5.1 Introduction

A copper heating coil is utilized to increase the temperature of feed water, vaporization, as well as condensation rates without increasing the projected area of solar still. The impact of using a DC fan, EC, and PCM will also be addressed in the sections. A number of parameters have been recorded during the experimentation i.e. solar radiations, yield of drinkable water, air speed, and temperature at different locations (glass cover, basin, PCM, water temperature).

5.2 Performance analysis of ASS using heating coil

The performance evaluation of ASS has been compared with that of CSS. Figures 5.1 and 5.2 indicate the hourly variation in solar intensity, glass cover temperature, air temperature, and basin water temperature (BWT) respectively. Average water temperature difference between ASS and CSS was noted as 0℃-12℃. It is because of copper heating coil that water is automatically fed into the ASS, and it is also observed that feed water temperature is higher in the range of 0-10℃ as compared to conventional SS. The maximum glass cover temperature and water temperature was recorded as 75℃ & 55℃ and 63℃ & 47℃ in ASS and CSS respectively at 13:00h. Similarly, the higher feed water temperature of ASS was noted as 55℃ at13:00h. The glass cover temperature for ASS revealed higher values than that for conventional SS by around 0 - 7℃ due to higher evaporation and condensation rates for ASS compare to CSS as a result of more water temperature for ASS. From Fig. 5.2, it was observed that the solar intensity fluctuated in the range of 0- 1070W/m^{2}K. The maximum solar radiation was noted as 1070W/m^{2}K at 12:00h and started decreasing thereafter.

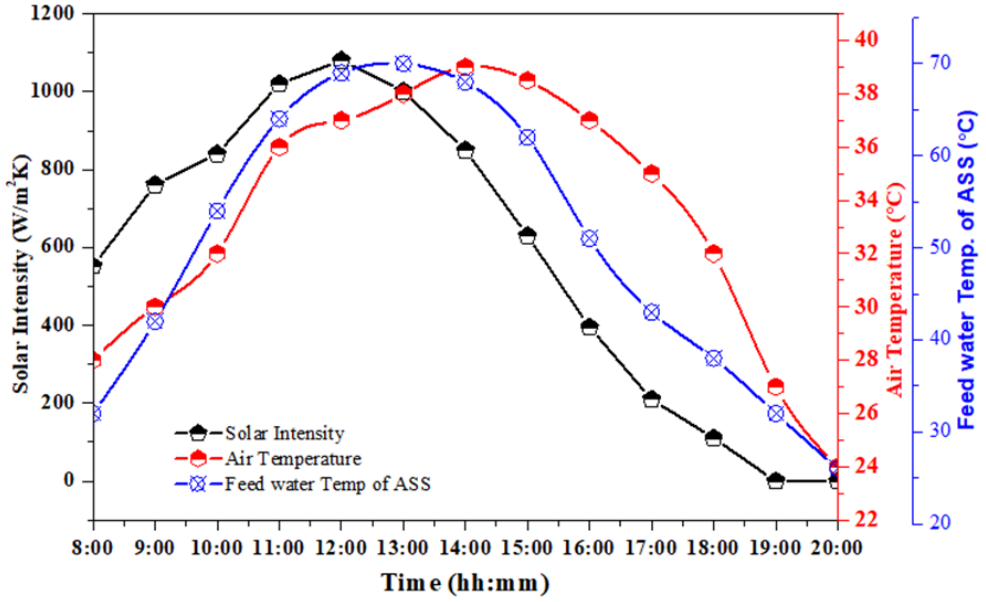


Figure 5.1 Variation in solar radiation, ambient temperature, and temperature of feed water

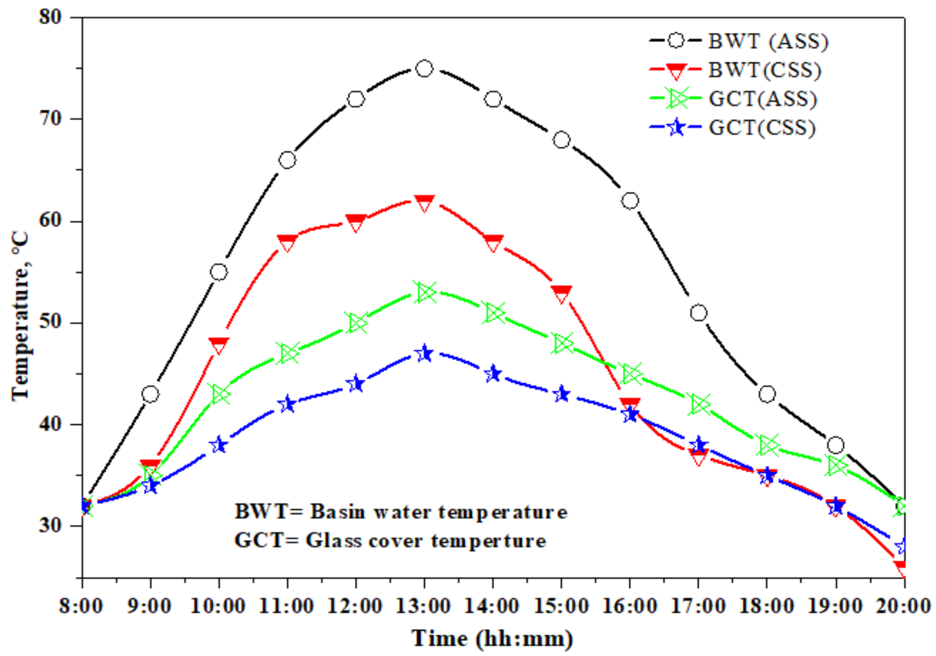


Figure 5.2 Variation in Basin water and glass cover temperature with the time of day for both systems

Hourly variation in yield for advanced SS and convention SS has been compared and displayed in Figure 5.3. The graph demonstrates that ASS regularly surpasses CSS in terms of daily productivity. It is because of higher BWT, evaporation, and condensation rates for ASS compare to CSS. The maximum yield of fresh water was achieved as 860 ml/m^2 and 485 ml/m^2 in ASS and conventional SS respectively at 13:00h. The cumulative yield of ASS (5500 ml/m^2) was attained nearly 77% more compared to that of conventional SS (3090 ml/m^2) as presented in Figure 5.3.

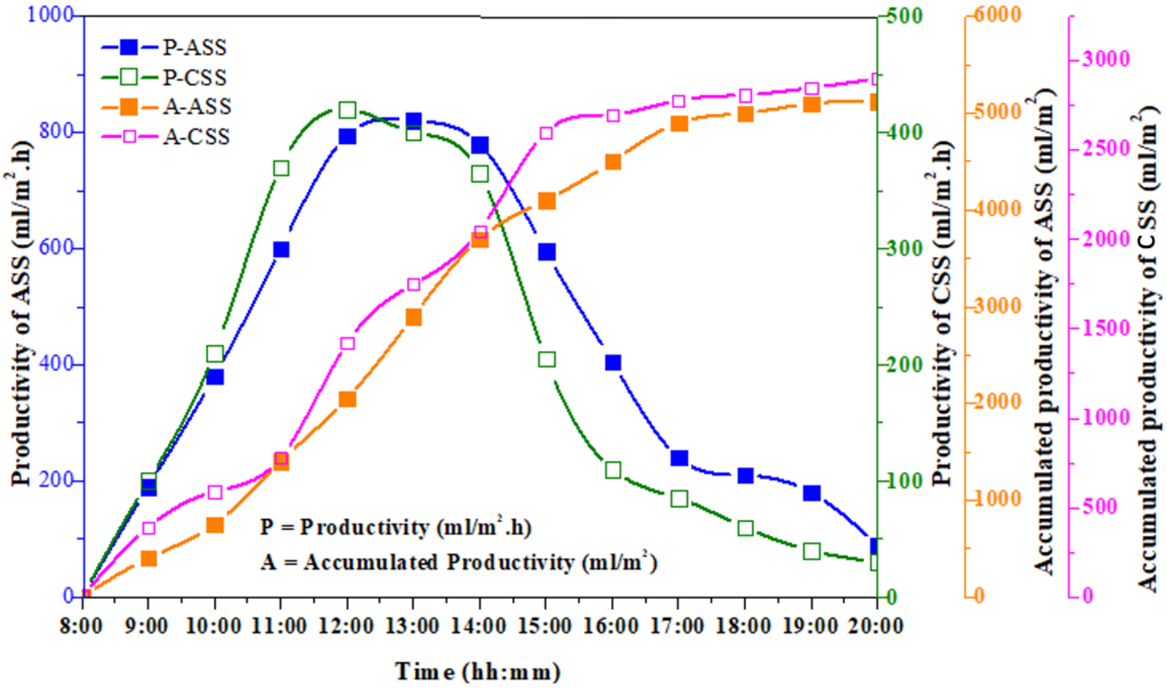


Figure 5.3 Hourly variation in productivity and accumulate productivity for ASS and CSS

5.3 Performance evaluation of ASS with heating coil and external condenser (ASS-EC)

The ASS's glass cover's temperature has been lowered using an axial DC fan and an external condenser to enhance the condensation process. With the employing of EC with heating coils, glass cover temperature and basin water temperature of ASS is increased in the range of 0-2°C and 0-7°C than that of CSS. It is because of suction fan decreases the internal pressure of ASS-EC, which reduces the saltwater temperature. Furthermore, the suction fan exhausts most of the water vapor inside the ASS to the EC. Therefore, some amount of low-temperature water vapor will condense on the inner surface of glass cover. Figures 5.4 and 5.5 demonstrate the hourly variation in solar intensity, glass cover temperature, air temperature, and BWT respectively.

Additionally, it was noted that the solar intensity fluctuated in the range of 0- 1090W/m^2K. The maximum solar radiation was noted as 1090W/m^2K at 12:00h and started decreasing thereafter. Higher water temperature and glass cover temperature were achieved as 71℃ & 51℃ and 62℃ & 47℃ in ASS-EC and CSS respectively at 13:00h. It was also observed that maximum basin water temperature (69℃) attained in ASS at13:00h and after that begins to go down.

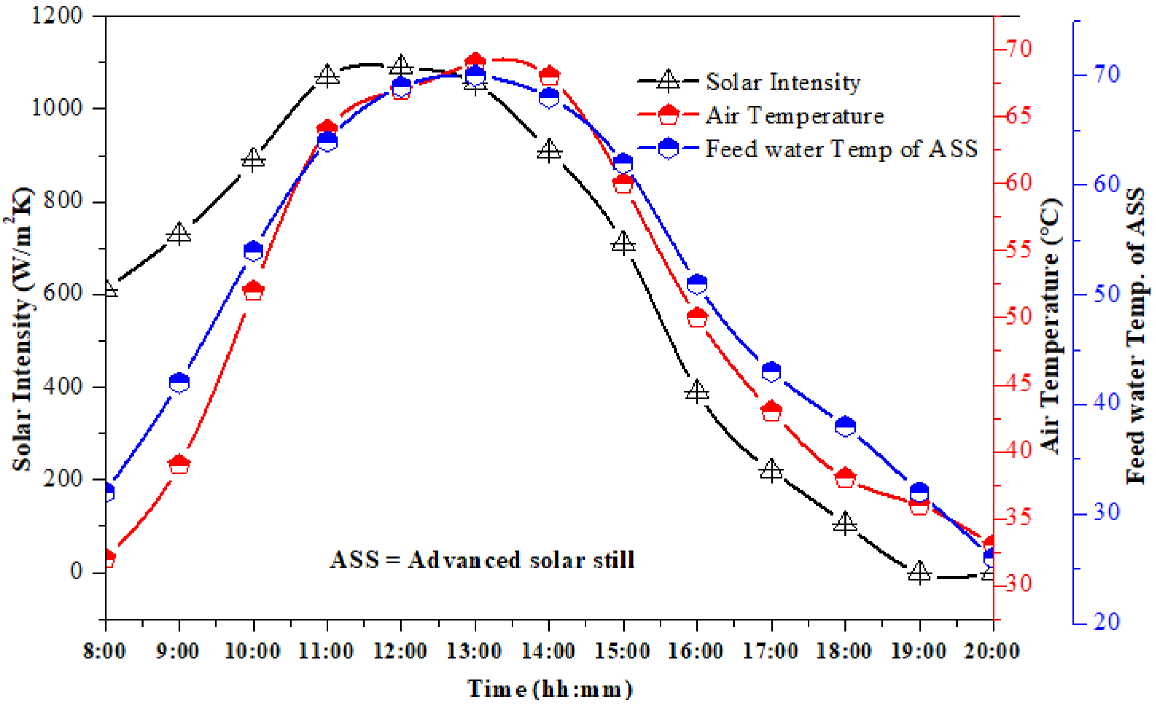


Figure 5.4 Variation in solar radiation, ambient temperature, and feed water temperature

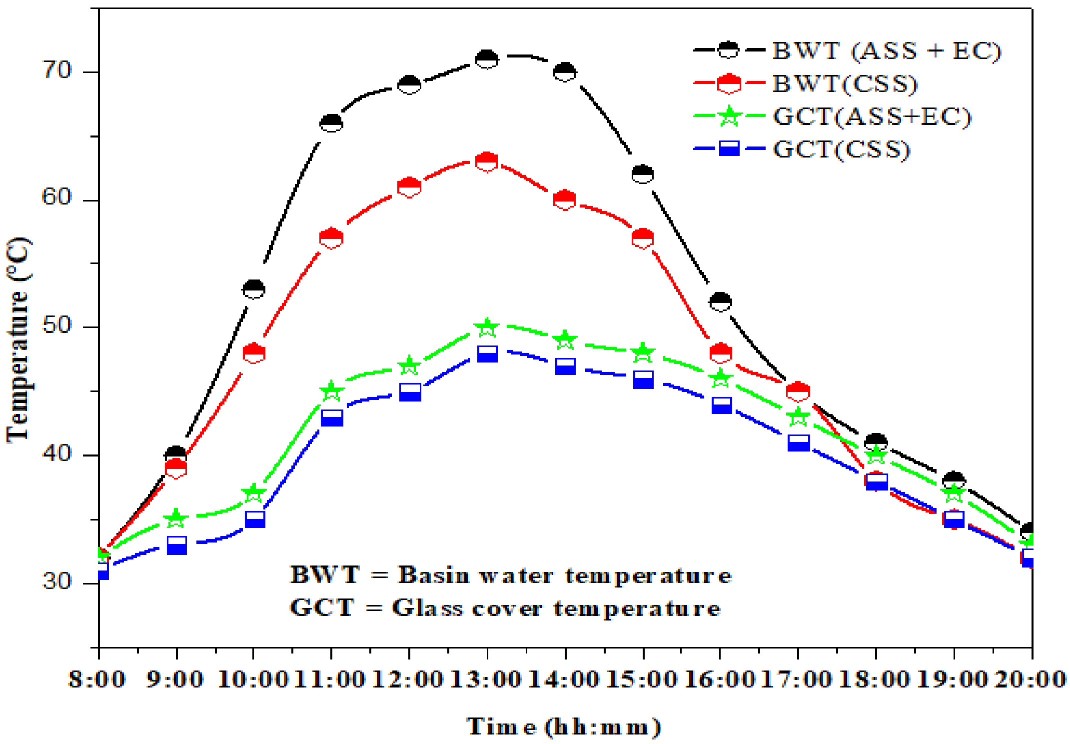


Figure 5.5 Variation in basin water and glass cover temperature for both systems

The variation of hourly yield for ASS-EC and CSS has been compared and displayed in Figure 5.6. The yield of fresh water reached 6800 ml/m^2 and 3200 ml/m^2 per day in ASS-EC and CSS respectively. Hence, ASS-EC has 119% more distillate production compared to CSS. This is mostly because having a fan, increases productivity and the suction fan, which circulates air inside the solar still above the salty water, accelerates evaporation by creating some turbulence. Furthermore, most of vaporized water from the saline water is drawn into EC by the suction fan.

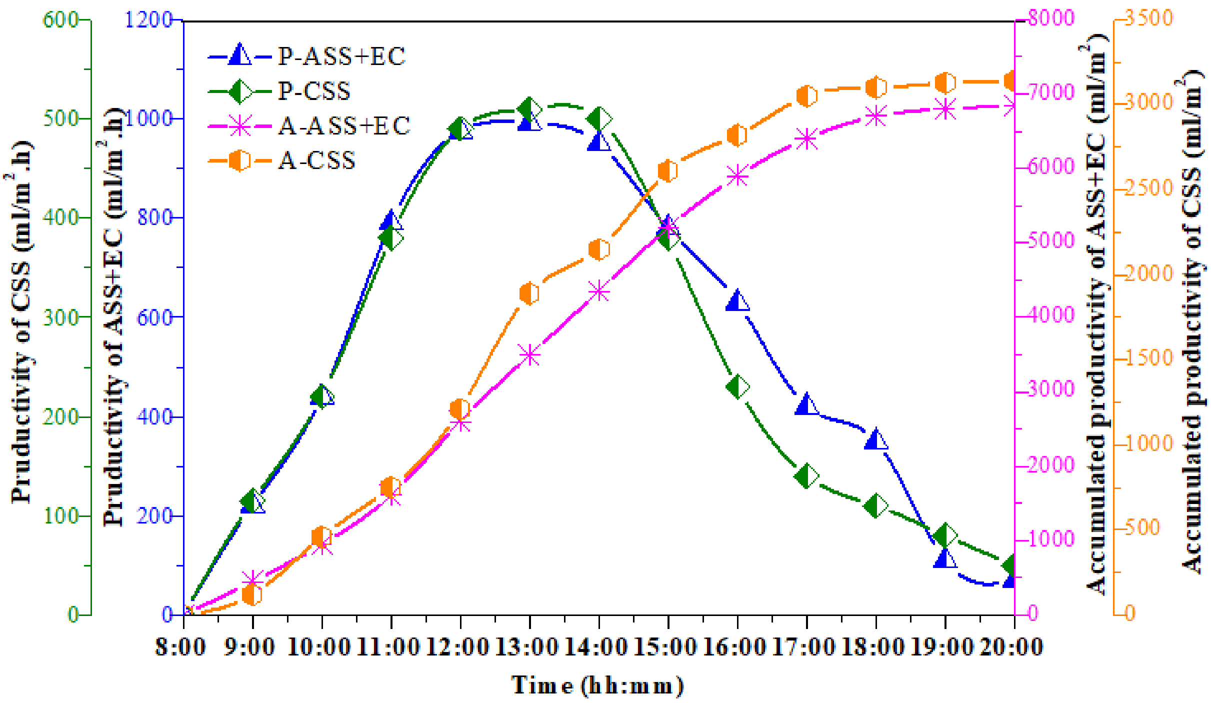


Figure 5.6 Hourly variation in productivity and accumulate productivity for ASS+EC and CSS

5.4 Performance analysis of ASS with heating coil and ZnO + PCM (ASS-PCM)

A mixture of phase change material (PCM) and ZnO nanoparticles, which act as thermal storage bed was employed beneath of absorber plate of ASS to enhance productivity. The experiment was conducted on ASS employing a heating coil and PCM to reduce the temperature of glass cover by storing energy during periods of high solar intensity as well as temperature and then releasing it again. Temperature plays a significant role in PCM during the charging and discharging process. Energy is stored as sensible and latent heat, respectively, depending on whether the PCM temperature is outside or inside the melting temperature limit. Energy is stored and released during the charging and discharging processes respectively. The variation of PCM and water temperature for ASS-PCM and CSS are demonstrated in Figure 5.7. PCM with ZnO nanoparticles has superior thermal conductivity and lower melting and solidification temperatures when compared to PCM without nanoparticles. Trends of the curve indicate that the temperature of water for ASS-PCM & CSS and temperature of PCM progressively increased from the early morning until about 13:00h and after that begins to reduce. The heat was transmitted from absorber to PCM before 13:00h, although after that time, the heat was transmitted from PCM to the absorber. Because after 13:00h, the temperature of PCM begins to drop till it achieves the atmospheric temperature. From Figure 5.7, it was concluded that the difference in water temperature between ASS-PCM and conventional SS was more during discharging period compared to during the charging period. It is because of heat being transmitted from PCM to the ASS-PCM absorber.

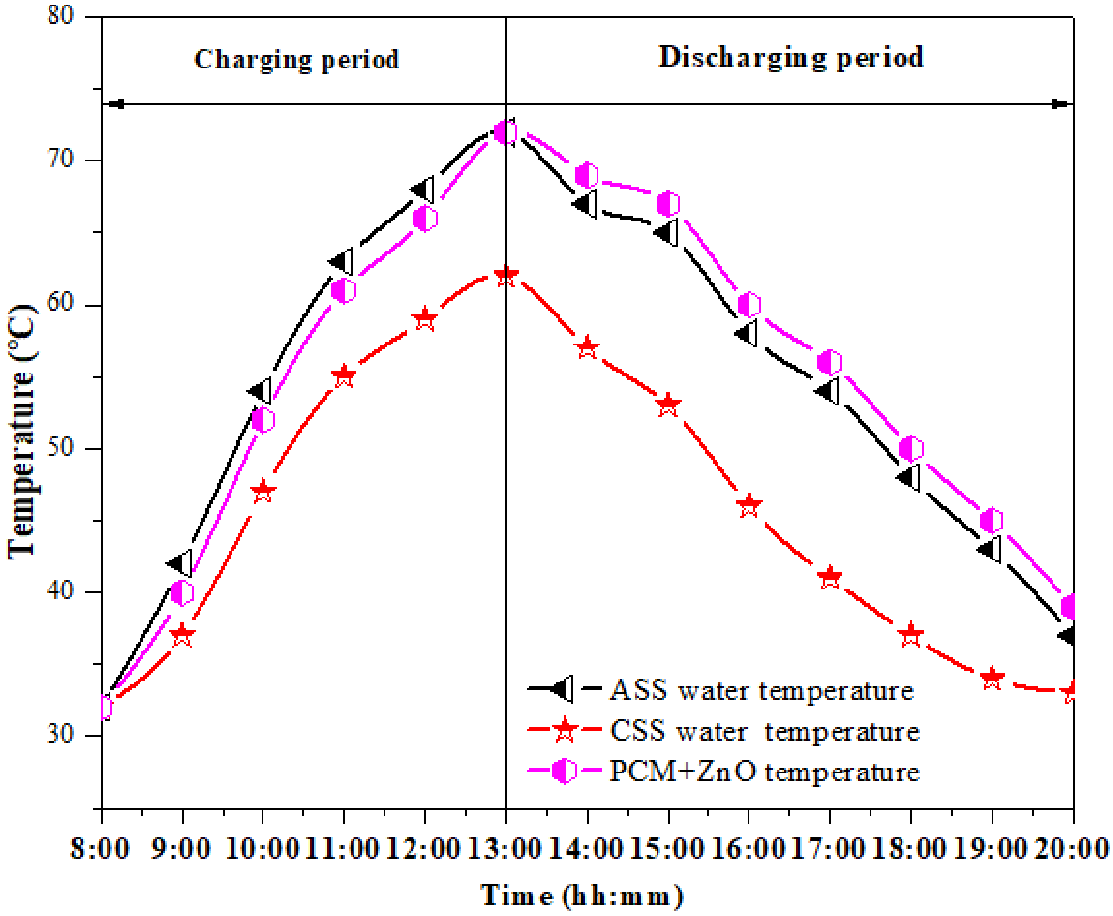


Figure 5.7 Variation in temperature for ASS, CSS, and ASS-PCM-ZnO

Figure 5.8 shows the hourly as well as cumulative productivities for ASS-PCM and CSS. The trends of the curve indicate that ASS-PCM constantly performs more efficiently compare to CSS in terms of yield during the experimentation. It is because of high BWT, evaporation, and condensation rates for ASS-PCM compared to that of conventional SS. The cumulative yield of

ASS-PCM (6600 ml/m^2) was attained nearly 113% more compared to that of conventional SS (3090 ml/m^2) as presented in Figure 5.8. As a result, the productivity of ASS-PCM has increased by about **36%** employing the PCM.

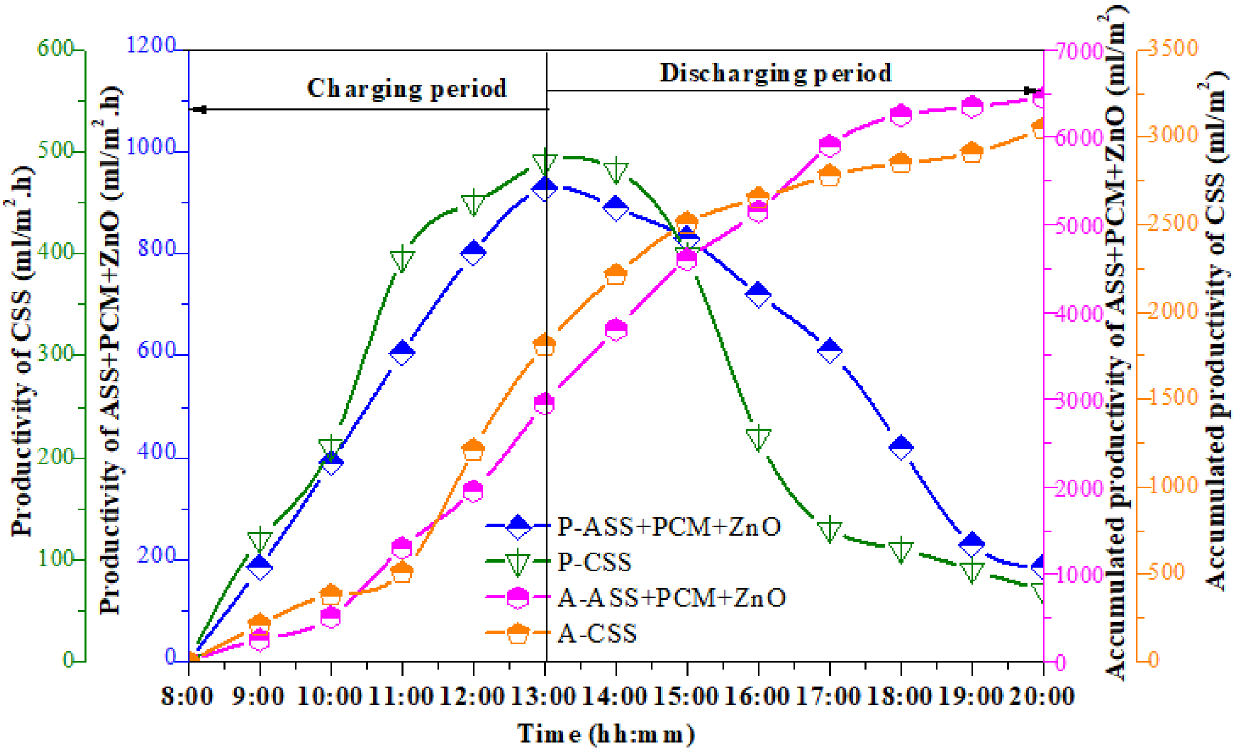


Figure 5.8 Representation of productivity and accumulated productivity

5.5 Thermal efficiency and increased yield of ASS

Thermal efficiency and fresh water yield play a significant role in the evaluation of thermal performance of SS system. The productivity improvement for ASS in comparison to CSS is shown in Figure. 5.6 as a percentage increase. Therefore, the representation of thermal efficiency for each case is demonstrated in Figure 5.9. Maximum thermal efficiency and improved yield are calculated as 46% & 77%, 53% &119%, and 51% & 113% for ASS (heating coil), ASS-EC, and ASS-PCM-ZnO respectively.

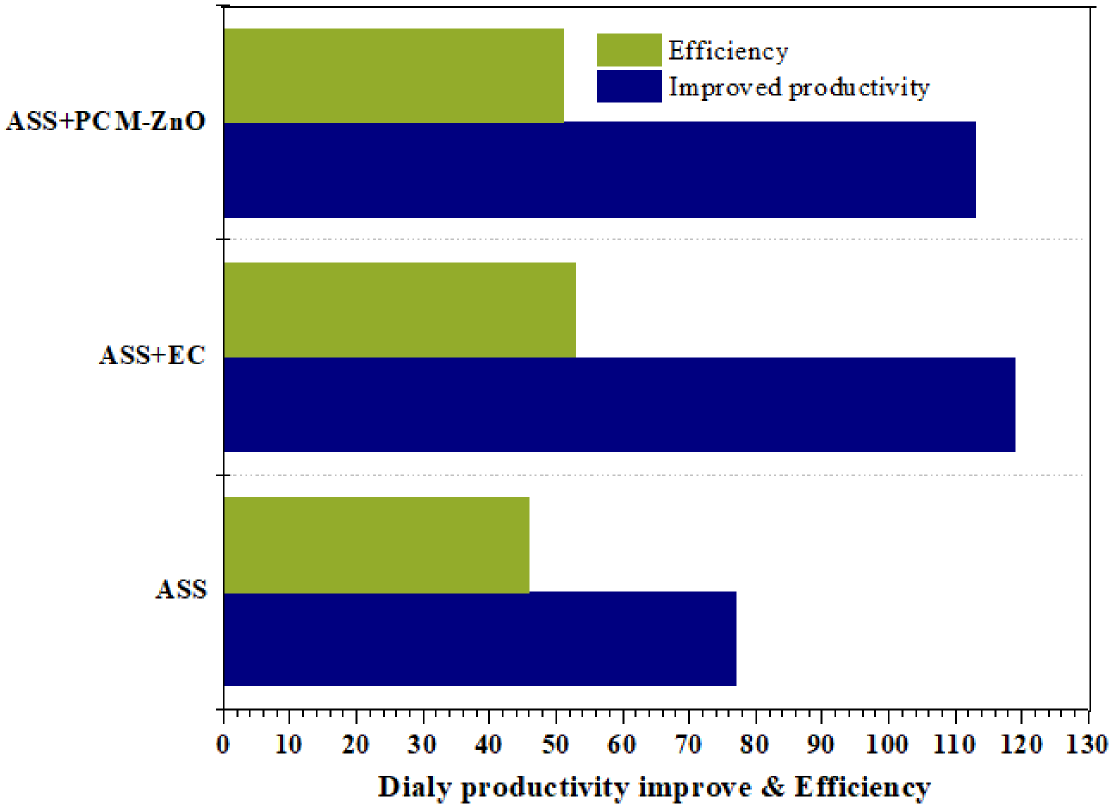


Figure 5.9 Relationship between daily productivity increase and efficiency

5.6 Calculation of cost analysis

The fixed prices of both ASS and CSS with different modifications are listed in Table 5.1. Furthermore, assumptions (no. of working days in a year, interest rate, and system lifetime) and estimates for variables used in economic analysis are discussed in Table 5.2. Desalinated freshwater's acquired prices were 0.030, 0.023, and 0.021 US$/l for the CSS, ASS-PCM, and ASS-EC, correspondingly.

Table 5.1 Fixed price of CSS and ASS

S.No	Materials	CSS (US$)	ASS (US$)
1.	Steel sheet	22	22
2.	Glass cover	19	19
3.	Iron stand and ducts	24	24
4.	Production	25	41
5.	Wood	25	25
6.	Thermocol	0.36	0.36
7	Oil paint	10	10
8.	Float	04	04
9.	DC fan		28
10.	Copper tube for heating coil		12
11.	Phase change material		10
12.	ZnO Nanoparticles		30
13.	PV panel		43
14.	Silicone gel	5	5
15.	Labor cost	12	12

Table 5.2 Price of different factors

Factors	Mean	Value			Unit
		CSS	ASS-EC	ASS-PCM	
n	System lifetime	15	15	15	Years
i	Interest rate per annum	12	12	12	%
N	Workings days per annum	340	340	340	Day
P	Setup fixed price	146.36	245.36	269.36	US$
M	Average production of desalinated water	1100	2450	2300	l/m^2 year
CPL	Price of desalinated water	0.030	0.021	0.023	US$/l
AMC	Annual maintenance cost	2.30	3.80	3.85	US$
ASV	Annual salvage value	0.55	0.92	0.93	US$

5.7 Environmental analysis

Environmental analysis plays a significant role in showing the impact of advanced solar still (ASS) systems on the atmosphere. Solar stills system is the best example of sustainable system and also does not affect the atmosphere in any manner. First step in environmental analysis is to calculate the embodied energy of both advanced SS and conventional SS. Table 4.4 specifies the amount of embodied energy for different used material to fabricate both systems. The calculated value of

EBPT, CO_2 Mitigation, Carbon Credit Earned, CO_2 Emitted, and Net CO_2 Mitigation (Lifetime) is in Table 5.3.

Table 5.3 Outcomes of environmental parameters

Environmental factors	**Unit**	**CSS**	**ASS**
EBPT	Year	2.20	2.50
Carbon Credit Earned	US$	6525.58	7520.12
CO_2 Emitted	kg/year	68.25	145.25
CO_2 Mitigation	kg/year	475.25	960.31
Net CO_2 Mitigation (Lifetime)	Tons	6.10	8.12

6.1 Conclusion

The experimentation work was carried out to compare the thermal performance, efficiency, and productivity of drinkable water in CSS and ASS (for all categories i.e. with heating coil, EC, and ZnO-PCM) under the identical metrological condition. The results demonstrate the following conclusion:

- To enhance the temperature of feed water as well as the condensation process, and lower the temperature of back side wall a copper heating coil was installed in the back wall of solar still.
- The cumulative yield of ASS using a heatig coil (5500 ml/m^2.day) was attained nearly 77% more compared to conventional SS (3090 ml/m^2.day).
- The yield of fresh water was obtained as 6800 ml/m^2 and 3200 ml/m^2 per day in ASS-EC and CSS respectively at 13:00h. Hence, ASS-EC has 119% more distillate production compared to CSS. As a result, the productivity of ASS has increased by about 42% employing the EC.
- The cumulative yield of ASS-PCM (6600 ml/m^2.day) was attained nearly 113% more compared to conventional SS (3090 ml/m^2.day) as presented in Figure 5.8. As a result, the productivity of ASS-PCM has increased by about 36% employing the PCM.
- The maximum thermal efficiency and improved yield are obtained as 46% & 77%, 53% &119%, and 51% & 113% for ASS (heating coil), ASS-EC, and ASS-ZnO-PCM respectively.
- CO_2 emission normally depends on the embodied energy of the material used for fabricating the solar still system. In ASS auxiliary devices are compared to conventional SS; it is observed that CO_2 emission is 52.83% more in ASS.

CHAPTER-VII
FUTURE SCOPE

7.1 Scope For Extending Research

Hence the scope for extending present research work is enormous. Few significant areas of extending present research work mentioned as:-

- Experiments can also do with different nano-particles such as Al_2O_3 and MgO etc.
- It can also do by changing the volume fraction.
- Energy, exergy, energy matrices, environeconomic and exergoeconomic assisted with different nanoparticles and nanofluids can be studied.
- The effect of mass flow rate, size, and shape of nanoparticles can be investigated.
- PCM materials other than paraffin wax can also be used to store energy in the daytime when the sun is shining, which can be further utilized when the sun is absent.

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LIST OF PUBLICATION

1. **Anil Kumar**, Anand Kushwah, Anil Kumar, "A novel reduced nano-phase change material based absorber for enhancing the water productivity and performance of solar desalination system", Materials Letters, Volume 341,2023,134298, ISSN 0167-577X, https://doi.org/10.1016/j.matlet.2023.134298.
2. **Anil Kumar**, Anand Kushwah, Anil Kumar, Experimental investigations on advanced solar still integrated with heating coil and nano-phase change material: A novel approach for sustainable development. Desalination and Water Treatment. Manuscript ID is TDWT-2023-0115 **(Under Review)**

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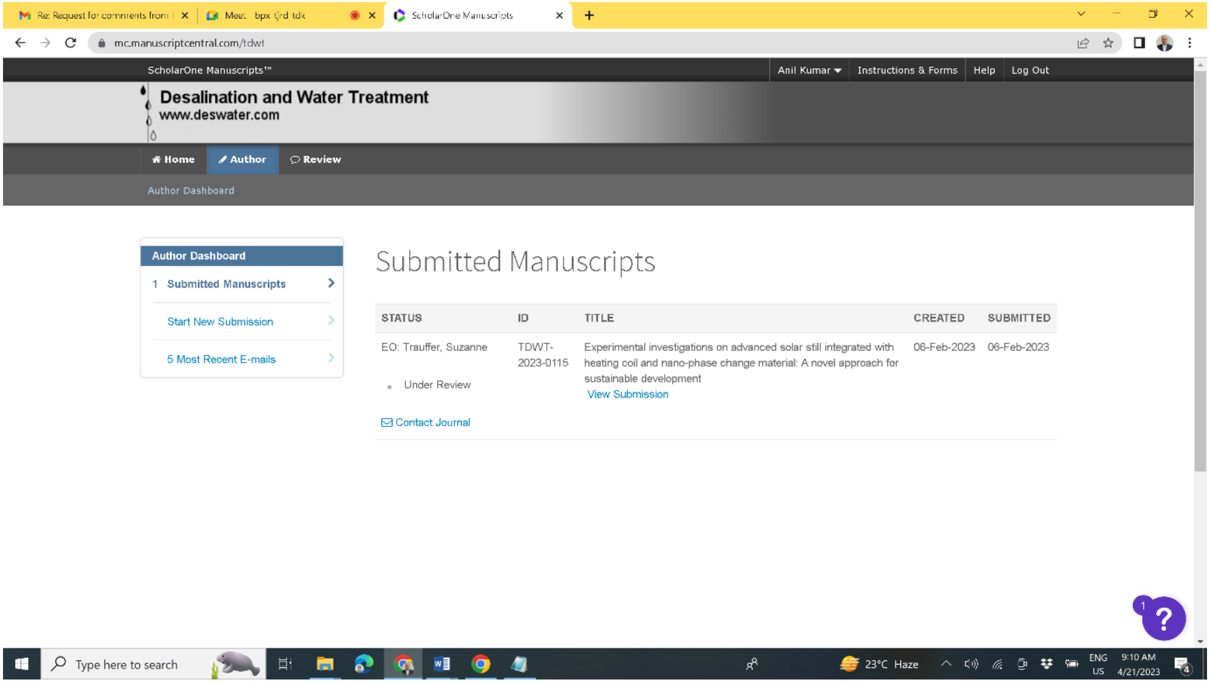
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A novel reduced nano- phase change material based absorber for enhancing the water productivity and performance of solar desalination system

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ABSTRACT

In present research work, two different types solar stills - conventional solar still and advanced solar still (ASS) have been studied. To enhance the yield (productivity) of ASS a nano-phase change material (ZnO-PCM) has been used. Conventional and advanced solar still performance is compared under same climatological conditions in two investigation sets. Maximum thermal efficiency and improved yield are obtained as 51% and 6600 ml/m^2 for ASS-ZnO-PCM, respectively. Thus, cmulative yield of ASS-ZnO/PCM (6600 ml/m^2) was nearly 113% more than conventional SS (3090 ml/m^2.day). As a result, the productivity of ASS-ZnO/PCM has increased by about 36% employing the PCM.

1. Introduction

Water is one of the amplest resources on earth, making up around 75% of the earth. However, a major crisis in many nations is inadequate water. Choosing a suitable and affordable desalination process is necessary to address the fresh water shortage. Sun's power is a more important renewable energy source and plays a significant role in solar water heating, cooking, drying, air heating, cooling, power generation, and water desalination. Among the earlier solar energy methods, solar water desalination is an efficient and attractive technique for providing drinkable water, which is the life of all living being [1]. Several techniques of solar water desalination have been studied and put for experiments. Amongst them, solar stills (SS) are more common, lower price, small scale, and existing system, which can be used to drinkable stock water for humans in arid regions. Number of studies have been carried out to improve productivity and thermal efficiency of SS systems. In addition, the performance of solar still systems has been improved by introducing reflectors, nanoparticles [2], phase change solar still. Among the aforementioned factors, applying nanoparticles to a brine has attracted much attention for enhancing solar intensity adsorption [3]. Different nanoparticles have been used for this purpose i. e. SiO_2, ZnO, CuO, Al_2O_3, CuO_2, TiO_2, Fe_2O_3, SnO_2, graphite, and SiC [4]. Sharshir et al. used graphite and CuO nanoparticles in SS to increase its yield. Productivity improved as 44.91% and 53.95% for CuO and graphite nanoparticles, respectively [5]. Elango et al. studied the effect of ZnO, SnO_2, and Al_2O_3 in single basin SS. Their findings revealed that productivity was 18.63%, 12.67%, and 29.95% more than without nanoparticle use [6]. Madhu et al. evaluated the performance analysis of CSS using CuO, TiO_2, and Al_2O_3 nanoparticles in brine water. The results indicated that solar still achieved maximum efficiency (50%) using Al_2O_3 nanoparticles [7]. Hasanianpour and Ameri developed a single slope SS and tested the performance of system using γ-Al_2O_3 nanoparticles in base fluid. It was observed from the findings that productivity of fresh water had increased up to 61% [8]. Recently, a variety of nanoparticles, namely Al_2O_3/Cu, Fe_3O_4/carbon, TiO_2/Cu, TiO_2/Ag, and CuO/graphene oxide (GO), have been synthesised and used to improve heat transfer rate in heat exchangers, solar stills, and other heat transfer equipment [9].

In current work, effect of nano-phase change material name paraffin wax (ZnO-PCM) on yield of advanced solar still (ASS) by adding a 20 mm ZnO-PCM nano-particle layer underneath the absorber plate and an external condenser with an electric fan was examined. The influence of different parameters, such as nano-phase change material concentration in base fluid and volume ratio of ZnO and PCM in hybrid nanocomposite, were also experimentally analyzed.

2. Materials and methods

The fabrication, installation, and procedure for the experiment are

Abbreviations: BWT, Basin Water Temperature; SS, Solar Still.

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Nomenclature

P_F	DC fan power
m_{np}	Mass of nanoparticles (gm)
η_d	Daily thermal efficiency (%)
A	Area of the system (m^2)
m_w	Mass of water (ml)
T_w	Temperature of water (℃)

discussed in this section.

2.1. Material used

A stainless steel sheet of 2 mm thickness (thermal conductivity 58 W/m^2K and density 7.80 g/cm^3), plywood of thickness 20 mm, and polystyrene (thermocol) of thickness 20 mm were brought from local market of Gwalior (India). Toughened glass of 4 mm thickness was used to enclose the system. Copper tube of 5 mm diameter was used to make a condenser on the back walls of solar still.

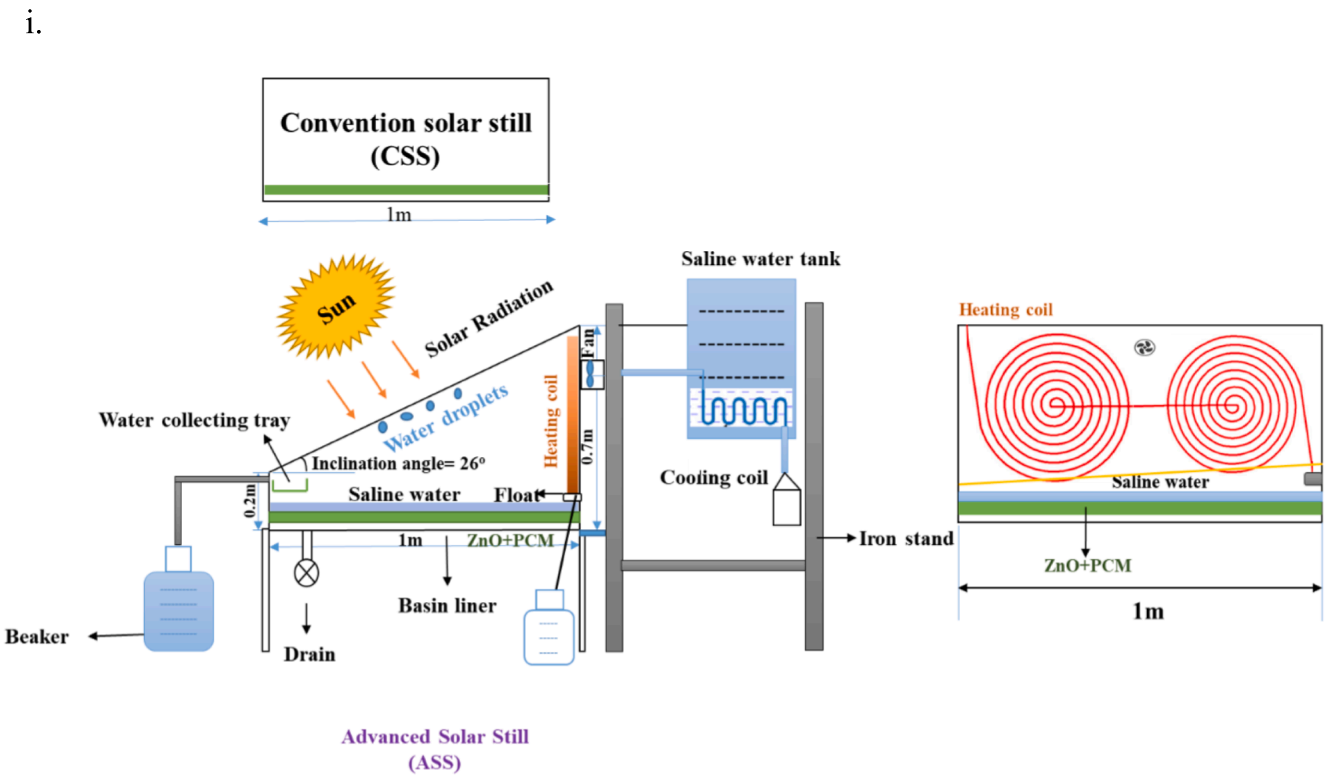

Fig. 1. Schematic view of experimental setup.

Table 1
Detailed description of experimental setup.

Component	Description
Solar still	
Plywood	20 mm (Thickness)
Thermocol (Polystyrene)	20 mm (Thickness)
Steel sheet	2 mm (Thickness)
Glass cover	4 mm (Thickness)
Iron stand	02 ((Thickness 5 mm)
Basin area	1 m × 1 m
Lower height	0.2 m
Height of back wall	0.7 m
Inclination angle	26°
Latitude of site location	26.2183° N, 78.1828° E
DC fan	
Types	06 W DC solar powered
Copper tube	
Length of copper tube heater	4 m
Diameter of copper tube	5 mm
Thickness of PCM-ZnO layer	20 mm

2.2. Methodology

In current research, two types of SS systems have been fabricated in the Madhav Institute of Science and Technology, Gwalior (India) solar energy lab. The first is considered a CSS, while the second is an advanced SS, as shown in Fig. 1. The CSS is used to build a stainless steel sheet of 2 mm thickness. A detailed description of CSS and ASS is discussed in Table 1. A toughened glass of 4 mm thickness enclosed the system and acted as a condensing surface. An inclined trough was attached to the lower edge of solar still for collecting the condensates water. In ASS, a 20 mm ZnO/PCM nano-particle layer is underneath the absorber plate.

2.3. Instrumentation for recording observations

i. Data-logger (Data Taker DT85 series 3, Australia) is installed and records relative humidity (Rh) and ambient air temperature. Experimentation work is carried out from 8:00 to 20:00hr.
ii. Anemometer (Dynalab DLAW 8701) measures airflow rate (m/s) over the glass cover of CSS and ASS.
iii. Solarimeter (Megger PVM 210) is mounted and used to record direct beam radiations and diffused solar radiations at regular intervals.

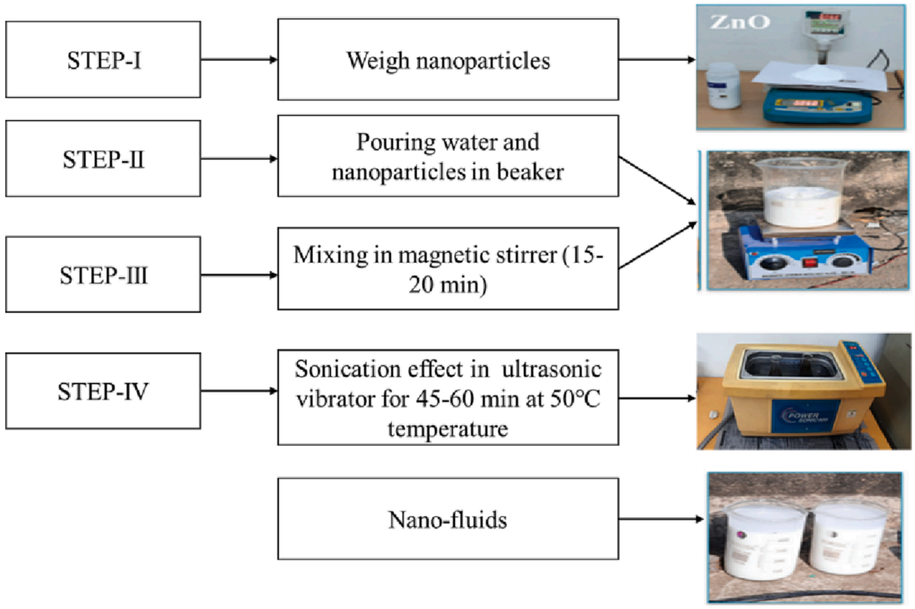

Fig. 2. Nano fluids preparation.

iv. K-type thermocouples are used to record the temperature.

2.4. Thermal efficiency of system

Thermal efficiency of solar still system can be calculated using the following relations [9]:

$$\eta_d = \frac{\sum m^{\cdot} \times h_{fg}}{\sum A \times I + P_F} \quad (1)$$

Latent heat of vaporization (h_{fg}) according to water temperature can be evaluated as [9]:

$$h_{fg} = 3.1625 \times 10^6 + \left[1 - \left(7.1616 \times 10^{-4} \times T_w\right)\right] \text{ for } T_w > 70\,^\circ C \quad (2)$$

$$h_{fg} = 2.4935 \times 10^6\left[1 - \left(9.4779 \times 10^{-4} \times T_w\right) + \left(1.3131 \times 10^{-7} \times T_w^2\right) - \left(4.7974 \times 10^{-9} \times T_w^3\right)\right] \text{ for } T_w < 70\,^\circ C \quad (3)$$

2.5. Nano-fluid preparation

Nanoparticles ZnO are hydrophobic in nature. To make nanoparticles hydrophilic some methodologies have been implemented. Fig. 2 demonstrate the step involved in preparation of Nano-fluids. Usually, it was observed that most researchers had adopted surfactants and dispersants to make nanoparticles solvable in water.

Boiling point temperature of water increases due to surfactants and dispersants, under which water will evaporate slowly. Concentration of nanoparticles is determined using Eq. (4) [9].

$$\varphi_{np} = \left(\frac{m_{np}}{m_{np} + m_w}\right) \times 100 \quad (4)$$

3. Results and discussion

3.1. Performance analysis of ASS with heating coil and ZnO + PCM (ASS-PCM)

A mixture of phase change material (PCM) and ZnO nanoparticles, which act as thermal storage bed, was employed underneath the absorber plate of ASS to enhance productivity. The experiment was conducted on ASS employing a heating coil and PCM to reduce the glass cover temperature by storing energy during high solar intensity and temperature periods and then releasing it again. Temperature plays a significant role in PCM during charging and discharging process. Energy is stored as sensible and latent heat, depending on whether the PCM temperature is outside or inside the melting temperature limit. Energy is stored and released during charging and discharging processes, respectively. The variation of PCM and water temperature for ASS-ZnO/PCM and CSS are demonstrated in Fig. 3(a). PCM with ZnO nanoparticles has superior thermal conductivity and lower melting and solidification temperatures than PCM without nanoparticles. Curve trends indicate that the temperature of water for ASS-PCM & CSS and temperature of PCM progressively increased from the early morning until about 13:00 h and then began to reduce. Heat transmitted from absorber to PCM before 13:00 h and heat transmitted from PCM to absorber later. It is because, after 13:00 h, PCM temperature begins to drop until it achieves the atmospheric temperature. The difference in water temperature between ASS-ZnO/PCM and conventional SS was more during the discharging than during the charging period (Fig. 3(a). It is because heat is transmitted from PCM to ASS-ZnO/PCM absorber.

Fig. 3(b) shows the hourly and cumulative productivities for ASS-ZnO/PCM and CSS. The curve trends indicate that ASS-ZnO/PCM constantly performs more efficiently than CSS in terms of yield during the experimentation. It is because of high BWT, evaporation, and condensation rates for ASS-ZnO/PCM compared to conventional SS. The cumulative yield of ASS-ZnO/PCM (6600 ml/m^2) was nearly 113% more than that of conventional SS (3090 ml/m^2), as presented in Fig. 3(b). As a result, the productivity of ASS-ZnO/PCM has increased by about 36% employing the PCM.

3.2. Thermal efficiency and increased yield of ASS

Thermal efficiency and freshwater yield play a significant role in the evaluation of thermal performance of SS system. Productivity improvement for ASS compared to CSS is shown in Fig. 3(b) as a percentage increase. Therefore, the representation of thermal efficiency for each case is discussed. Maximum thermal efficiency and improved yield are calculated as 51% and 113% for ASS-ZnO/PCM, respectively.

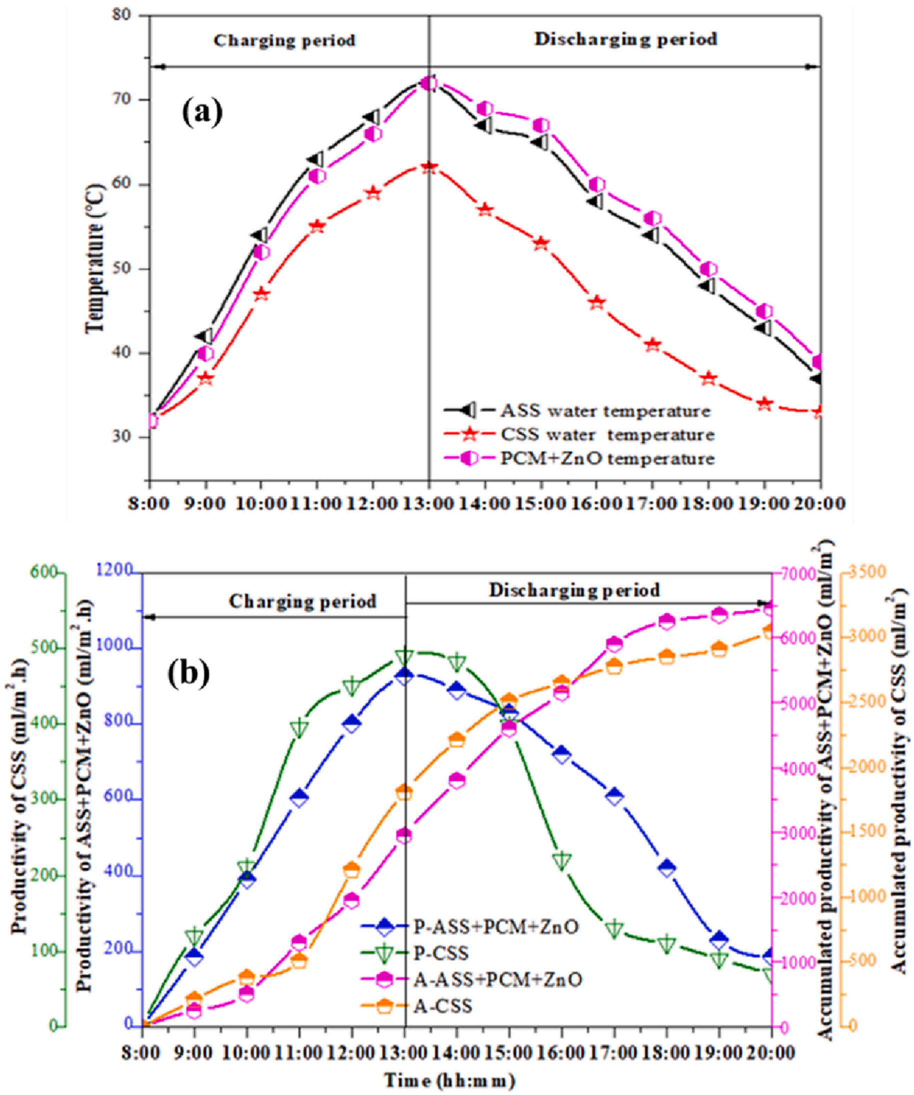

Fig. 3. **(a)** Variation in temperature for ASS, CSS, and ASS-ZnO/PCM, **(b)** Representation of productivity and accumulated productivity.

4. Conclusions

The experiment was performed to compare the thermal performance, efficiency, and productivity of fresh water in CSS and ASS (for ZnO/PCM) under identical metrological conditions. The results demonstrate the following conclusions:

- Cumulative yield of ASS (5500 ml/m^2.day) was nearly 77% more than conventional SS (3090 ml/m^2.day).
- Cumulative yield of ASS-ZnO/PCM (6600 ml/m^2) was attained nearly 113% more than conventional SS (3090 ml/m^2.day). The productivity of ASS-ZnO/PCM has increased by about 36% employing the PCM.
- Maximum thermal efficiency and improved yield are obtained as 51% and 113% for ASS-ZnO/PCM, respectively.

CRediT authorship contribution statement

Anil Kumar: Methodology, Writing – original draft, Investigation. **Anand Kushwah:** Investigation, Conceptualization, Formal analysis, Validation. **Anil Kumar:** Conceptualization, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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