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Studies On PCM Based Solar Desalination System

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ABSTRACT - The only nearly inexhaustible sources of water are the oceans, which are of high salinity. However, the separation of salts from seawater requires large amounts of energy, which, when produced from fossil fuels, can cause harm to the environment. Therefore, there is a need to employ environmentally friendly energy sources in order to desalinate seawater. In the present work, a solar still is fabricated and used for water desalination (removing salt content from water using solar energy). Probably, they are considered the best solution for water production in remote, arid to semi-arid areas. Where fresh water is unavailable, however, the amount of distilled water produced per unit area is somewhat low in the designed solar still, which makes the solar still unacceptable in some instances. The purpose of this present work is to study the effect of using phase change materials in a solar still and thus enhance the productivity of water. Bitumen is selected as a phase change material that is used to store the solar thermal energy in the form of latent heat, which can offer a high heat energy storage capacity per unit volume and per unit mass and it also provide heat energy at night time for desalination.

Keywords: Solar still, Distillation, PCM, water desalination, Bitumen, Latent heat

I. INTRODUCTION

Solar distillation uses the heat of the sun directly on a simple piece of equipment to purify water. The equipment, commonly called a solar still, consists primarily of a shallow basin with a transparent glass cover. The sun heats the water in the basin, causing evaporation. Moisture rises, condenses on the cover, and runs down into a collection trough, leaving behind salts, minerals, and most other impurities, including germs. Although it can be rather expensive to build a solar still that is both effective and long-lasting, it can produce purified water at a reasonable cost if it is built, operated, and maintained properly. Solar still works on the following two principles: evaporation and condensation.

Evaporation: First, the water that needs to be purified is placed in the trough with the black bottom. The solar still is then allowed to sit in the sun, which allows the still to absorb the sun's short-wave energy. As the energy is absorbed, it starts to heat the water. As the temperature of the water rises, the water is converted into steam and evaporates towards the glass ceiling, leaving anything that is not pure in the trough below.

Condensation: The second scientific principle on which a solar still acts is condensation. After the water begins to evaporate, it hits the glass ceiling. The water slowly condenses on the glass, causing pure water droplets. Since the glass is angled down towards the second trough, the water droplets toll down and into the clean water trough. Because none of the minerals, bacteria, or other substances are able to evaporate with the pure water, the water droplets that end up in the second trough are simply purified and are not safe for drinking or cooking.

Classification of Solar Stills

Solar stills are broadly classified into two groups called active and passive solar stills. Active solar still are integrated with solar collectors, heating units, and PV modules. The passive solar stills are classified based on their various designs. Figure 1 shows the major and subclassifications of solar stills.

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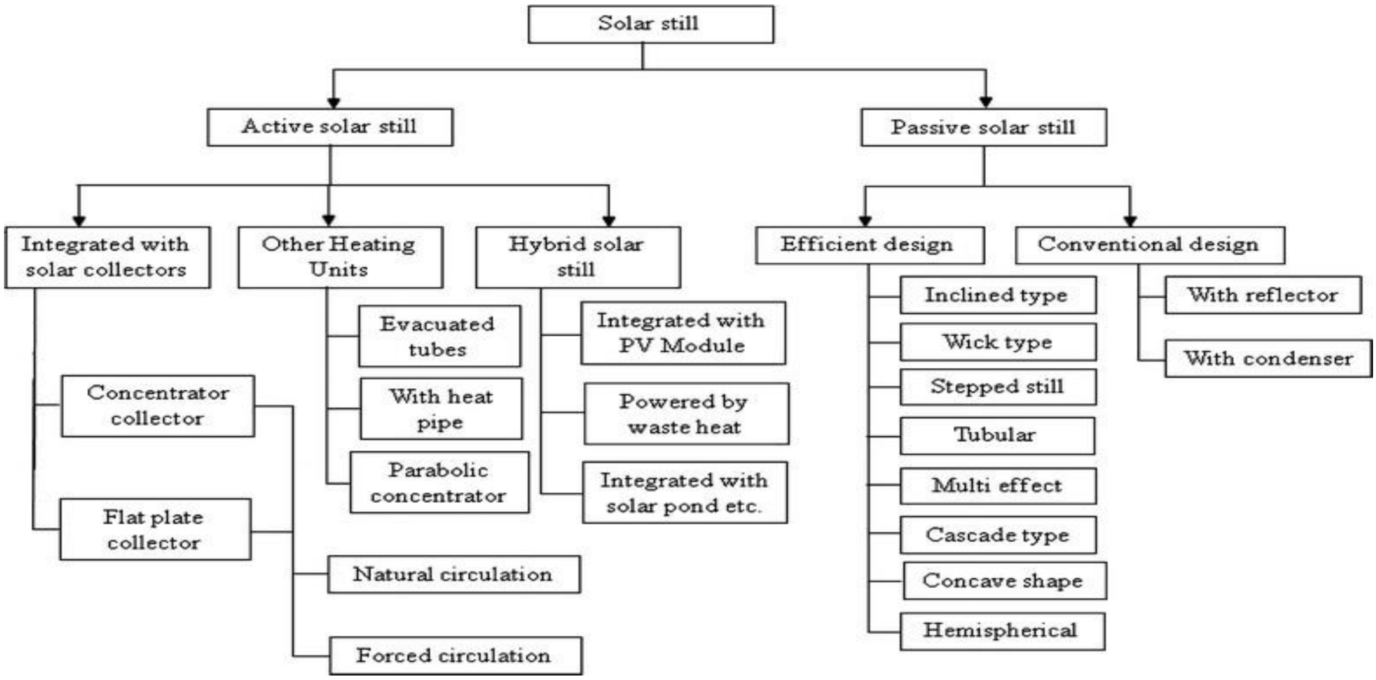

Figure 1 Classification of Solar Stills

Dunkle RV (1961) has done the experimental investigation on solar water distillation. In this study, a parabolic solar trough is coupled with a custom-designed distillation device. The incoming solar radiation from the sun is focused and concentrated onto a receiver pipe using a parabolic trough, heating the incoming impure water, at which point it is sprayed into our custom-designed distillation device, where it evaporates and is re-condensed into pure potable water. Sampthkumar et al. (2007) have done an experimental study on a single basin solar still augmented with evacuated tubes to increase daily productivity by reducing heat losses. Evacuated tubes were directly coupled to the lower side of the single-slope solar still with an area of $1m^2$. Black gravel is used to increase productivity by reducing the quantity of water in the basin. Extensive experiments were conducted to explore the performance of solar stills in several modes, namely still alone, still with black stones, still with evacuated tubes, and still with evacuated tubes and black gravel.

Mufag Suleiman K. Tarawneh (2007) has studied the effect of water depth on the performance evaluation of solar stills. The effect of water depth in the basin on water productivity was evaluated. At the same time, the effects of design and operational parameters on the solar desalination process were investigated. Sampathkumar et al. (2011) have made arrangements to couple the water-in-glass evacuated tubes with a single basin solar still. Even though many active methods have been developed to increase the productivity of the solar still, this technique has increased the daily average production to 72%. For high-temperature distillation, evacuated tubes have better performance when compared to flat plate collectors and other solar collectors. A thermal model was developed using energy balance equations, and the results obtained were in good agreement with the experimental results. This system's payback period is 235 days, based on the economic analysis.

Teltumbade and Walke (2011) have done an experimental evaluation of a single-basin solar still using different absorbing materials. They have used bitumen as a phase change material to store the solar thermal energy in the form of latent heat, which can offer a high storage capacity per unit volume and per unit mass, and they got heat in the night time for desalination. The efficiency of the solar still without PCM is about 25.19%, and in the presence of PCM, it is 27%. Alpesh Mehta (2011) has done the theoretical and experimental studies of a solar distillation in a single basin. An aluminum reflector was assembled on the still to obtain extra solar energy, and the effect of the reflector on the still's productivity was examined. In their theoretical study, they described the energy balances for the glass cover, seawater interface, black plate at the bottom, and overall still dimensions for finding still productivity.

Kantesh et al. (2012) have tried to enhance the solar still productivity using PCM and by varying the angle of the solar still from the ground surface. The experimental results illustrated that the use of PCM and angle variation with solar still is cost-effective and viable for enhancing the evaporation rate as well as thermal conductivity. Dwivedi and Tiwari (2013) have done experimental validation of the thermal model of a double-slope active solar still in circulation mode. A new thermal model and characteristics of double-slope solar stills (DSSS) have been developed. Experimental and theoretical results have been compared for the composite climate of New Delhi,

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India. Theoretical results obtained by previous and new thermal models of DSSS have been found to be in fair agreement with experimental observations.

Eze and Ojike (2012) have developed low-cost, basin type passive solar stills for the poor rural dwellers of Nigeria along the coastal areas. A comparative evaluation of two basin type passive solar stills was undertaken by distillation of salty water. The solar stills were rectangular-shaped and pyramid-shaped. Both stills were made of the same material and of the same size. The top of the rectangular-shaped type is sloped and inclined 22° to the horizontal in the north-south direction. The temperature analysis of the systems shows that during the day, the rectangular-shaped still performed better, giving a higher basin and subsequent higher saline water temperature with a lower glazing temperature when compared to the pyramid-shaped with a lower basin and saline water temperature but with a higher glazing temperature. The rectangular-shaped solar still gave an average efficiency of 36.8%, while the pyramid-shaped type performed at 28.9% efficiency. Hence, the rectangular-shaped solar still, in comparison with the pyramid-shaped type, is recommended for use by people, especially those living in coastal areas.

Amitava Bhattacharyya (2013) has made to the some modifications in solar still for high output using minimum areas of land and even on cloudy days. One such upgraded version is capillary stills, which are gaining popularity for their high output. The heart of a capillary still is a fabric that facilitates rapid evaporation of water at minimum heating. An overview of solar stills and capillary solar stills is discussed in this article. El-Sebaey (2013) has designed, fabricated, and tested a double-slope solar still with external flatted and internal parabolic reflectors and also optimized the external flat reflector tilt angle for Egyptian climatic conditions. The external flat reflector was tilted at 30°, 45°, 60°, and 75° on the horizontal plane. The depth of water inside the basin is 1cm. Experimental results were compared with conventional double-slope solar stills. The optimum tilt angle is found to be 60°, with a maximum daily productivity of 9.89 liter/m^2.

Chendake (2015) has designed and developed a double-slope type solar distillation unit. The designed model produces 1.6 liters of pure water from 12 liters of dirty water in eight hours. The TDS in pure water is 30 ppm. The efficiency is 22.33 % at a water depth of 0.02 m. Abdallaha et al. (2015) have studied the effect of various absorbing materials on the thermal performance of solar stills. The results are obtained by evaporating of the dirty or saline water and fetching it out as pure or drinkable water. The designed model produces 1.5 liters of pure water from 14 liters of dirty water in six hours. The efficiency of the plant is 64.37%. Kanika Mathur (2015) has fabricated a solar still that can produce a sufficient amount of distilled water on a daily basis to cater to the needs of lead-acid battery retailers, and thus saving on conventional sources of energy and also reducing the cost of distilled water for the retailers. The external reflector is used to increase the amount of solar radiation incident on the solar still, leading to an increase in the evaporation process. The rate of evaporation depends on the intensity of the solar radiations incident on the solar still.

Shristhi Shrestha et al. (2016) have studied the performance evaluation of a solar still. This paper takes a review of the latest developments in solar distillation systems. Abdulhaiy (2016) has studied the transient performance of a stepped solar still with built-in latent heat thermal energy storage. A single asymmetrical, automatic feed solar distiller was designed to take advantage of the solar energy available in the regions, such as Somalia, Africa. During this process, factors that will optimize single-day productivity while minimizing costs have been explored. All aspects that will affect clean water output have been analyzed including the effect of surface area on productivity, material selection and analysis, overall thermal efficiency, and the potential effectiveness of an automatic water feed system. Factors that will directly impact the overall build cost per unit have also been evaluated, such as material selection, size, and simplicity. The final design adds numerous features to increase the efficiency of a basic asymmetrical solar still. Jarel Robinson et al. (2016) have done an experimental study of a wide range of stills and their optimum design, construction, and performance. They have created a cost-efficient solar-still desalination model that can be used anywhere in the world, especially in developing countries that currently lack the infrastructure and resources to provide clean water to residents. The system designed in this study was able to effectively evaporate water in the first step of the purification process.

Seyed Sina et al. (2021) have designed the PCM chambers and they were constructed, fixed to the stepped solar still to improve the productivity rate and stored latent heat during the sunrise which expands the distilled water production time after sunset. Besides, an external condenser has been fabricated to investigate its impact on the performance of the stepped solar still. The experiments have been carried out under the same Iranian climate conditions. For the analysis, four cases have been considered, namely Case I: single stepped solar still, Case II: stepped solar still with an external condenser, Case III: stepped solar still with PCM, and Case IV: stepped solar still with external condenser and PCM. The comparison between four cases of experiments demonstrates the effectiveness of using an external condenser and PCM in stepped solar still.

Reji kumar et al. (2022) have done the review on Phase Change Materials integrated solar desalination system.

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This review analyzes the effect of wind, depth of water, the thickness of PCM, and highlights the improvement techniques of various active and passive solar still with and without PCM. Furthermore, it highlights the effect of nanoparticles enhanced PCM integrated solar still with different absorber designs and configurations. The reviews shows that the maximum freshwater production is 13.62, 15.39, and 18.6 L/m^{2}day for Evacuated tube collector (ETC) integrated solar still, parabolic trough collector integrated solar still, solar still with PCM-graphite nanoparticles, and solar still with PCM-graphene oxide nanoparticles, respectively.

In the present work, Bitumen is used as a phase change material to store the solar thermal energy in the form of latent heat, which can offer a high storage capacity per unit volume and per unit mass. This phase change material changes its phase from solid to liquid and stores solar energy; during liquid to solid, it will release absorbed solar energy. It is possible to get heat from the PCM in the night time for desalination. Bitumen is the oldest known engineering material and has been used since the earliest times. Bitumen is a non-crystalline, highly viscous material, black or dark brown, sticky, which is substantially soluble in carbon disulfide (CS_2), possessing adhesive and water-proofing qualities, and composed primarily of highly condensed polycyclic aromatic hydrocarbons.

Bitumen is a mixture of organic liquids and a complex mixture of a large number of high molecular weight organic compounds made by the processing of petroleum crude oils. At ambient temperatures, bitumen is a stable, semi-solid substance. Molecular weight wise, bitumen is a mixture of about 300-2000 chemical components, with an average of around 500-700. Elementally, it is around 95% carbon and hydrogen (± 87% carbon and ± 8% hydrogen), and up to 5% sulfur, 1% nitrogen, 1% oxygen, and 2000 ppm metals. The photographic view of the semi-solid bitumen is shown in Figure 2.

Figure 2 Bitumen in solid state

Bitumen grade 60/70 is one of the primary products obtained from crude oil distillation and is mostly used to pave roads. In the present study, bitumen of 60/70 grade is used. Table 1 shows the thermo-physical properties of paving-grade bitumen. These specifications were obtained from laboratory tests conducted by Mangalore Refinery and Petrochemicals Limited (MRPL), a subsidiary of ONGC. It is seen from table 1 that bitumen melts at 68°C. Bitumen is not a single element like ice, so it melts non-congruently.

Table 1 Thermo-Physical Properties of the Bitumen

Property	Value
Melting point	68°C
Latent heat of fusion	450.367 kJ/kg
Density (solid phase)	1030 -999kg/m3
Density (liquid phase)	724.6376 kg/m3
Specific heat (solid phase)	2.093 kJ/kg °C
Specific heat (liquid phase)	2.87 kJ/kg °C
Thermal conductivity (solid	0.17 W/m C
Thermal conductivity (liquid	0.074432 W/m °C
Boiling Temperature	> 525°C
Viscosity	25 – 400 Pa S

II. EXPERIMENTAL SETUP

Figure 3 shows the schematic of the experimental setup.

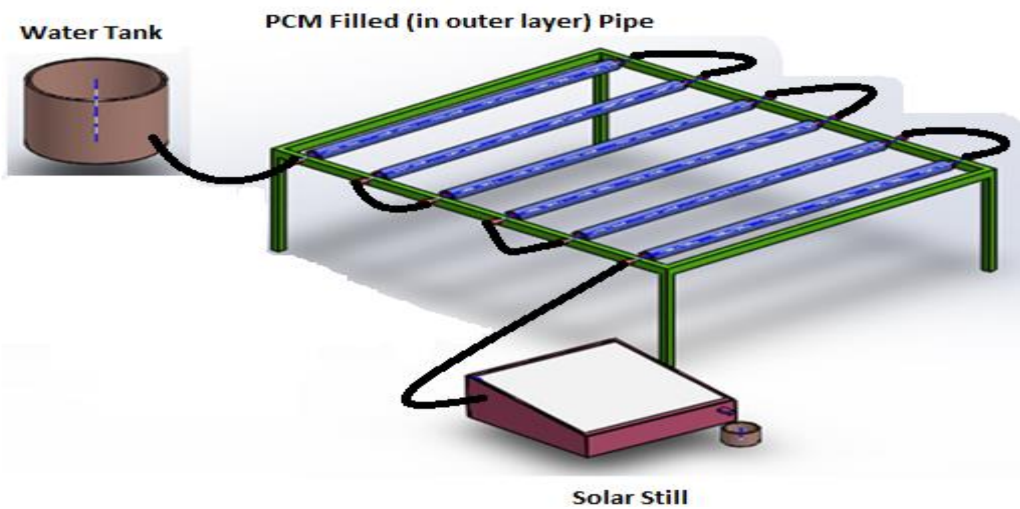

Figure 3 Schematic of the experimental setup

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Specification of PCM incorporated solar heater

- Outer Pipe Diameter - 44mm
- Inner Pipe Diameter - 22mm
- Outer Pipe Length - 915mm (6 Pipes)
- Inner Pipe Length - 1066mm (6 Pipes)
- Phase Change Material (BITUMEN) – 10 kg

Specification of Solar Still

- Glass Cover - (1000×520) mm
- Tank Length - 1000mm
- Tank Breadth - 520mm
- Tank Heigth Upper Side - 200mm
- Tank Heigth Lower Side - 100mm

The efficiency of solar still is calculated by using this formula:

$$H=ML/IAT$$

Where,

M-Mass of the distilled output (ml/hr)

L-Latent heat of water (kJ/kg)

A-Absorber area (m^2)

T-Time (sec)

I-Global radiation (W/m^2)

The solar still is made with a 2 mm thick alloy steel sheet and has dimensions of 1000 mm length and 520mm width. It has a height of 200mm on one side and 100mm on the opposite side, which tends to give an inclination of about 45°. Black-coated glass is covered above the solar still, which helps the glass cover condensate the water easily during evaporation. The distillate Channel is placed at the lower height, just below the inclined glass cover, in order to collect the water droplets. The photographic view of the solar still is shown in Figure 4.

Bitumen is a phase change material for storing solar radiation in the form of latent heat, thus it is filled in the pipes. The bitumen is filled in the annular space between 44 mm and 22 mm diameter pipes. The bitumen is heated up to 65°C to change from solid to liquid and thus poured into the annular pipe, and sudden cooling is made to change the liquid bitumen to a solid state. Both ends of the annual space are closed by welding. Similarly, six pipes are prepared with a length of 915mm each. Thus, the pipes are placed on the inclined stand in order to flow the water from the tank. All the inner pipes are joined, with one end as an inlet and the other as an outlet. The photographic view of the PCM incorporated pipe is shown in Figure 5.

Figure 4 Photographic view of the Solar Still

Figure 5 Photographic view of the PCM incorporated pipe

The water from the storage tank first enters the PCM-incorporated pipe. The PCM absorbs heat energy from solar radiation and converts it from solid state to a liquid state. The PCM absorbs heat energy from solar radiation and converts it from solid state to a liquid state. The absorbed energy gives heat energy to the water to raise its sensible heat, which is flowing inside the pipe. Then the hot water from the pipe is flowing into the solar still. The solar still is a simple device for obtaining potable water from contaminated or saline water using solar energy. It consists of a blackened tray containing saline water, covered with a sloping glass roof. Solar energy, which is transmitted by the glass cover and is absorbed by the water and also the black coloured basin, heats the water. This absorbed energy is conducted through the haze, radiated, convected to the glass cover, or carried by the evaporation of water to the glass cover. The cover is substantially transparent to solar radiation and opaque to infrared radiation, and serves as a condenser for the saturated vapour within the still. The glass cover transfers heat to the surroundings through radiation from the sky and convection with the ambient air. The water condenses on the inner surface of the glass cover, flows into the collection troughs due to gravity. Pure water is removed as a product.

The experiments are conducted for various levels of water in the solar still, i.e., 3, 4 & 5 cm of water level in the solar still, and also with and without PCM in the water pipe. The temperature of the water, glass cover, ambient, PCM temperature, and global radiation vs. time were

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taken. The experiments are conducted from 9:00 a.m. to 7:00 p.m.

III. RESULTS AND DISCUSSION

Figure 6 shows the global radiation from 9:00 a.m. to 7:00 p.m. on a solar still of a typical day. The solar radiation gradually increases from 9:00 a.m. and reaches a maximum value of 810 W/m^2 at 2:00 p.m. Thereafter, the solar radiation is slowly decreases until 5:00 p.m. After 5:00 p.m., it decreases at a faster rate and reaches a value of 150 W/m^2 at 7:00 p.m.

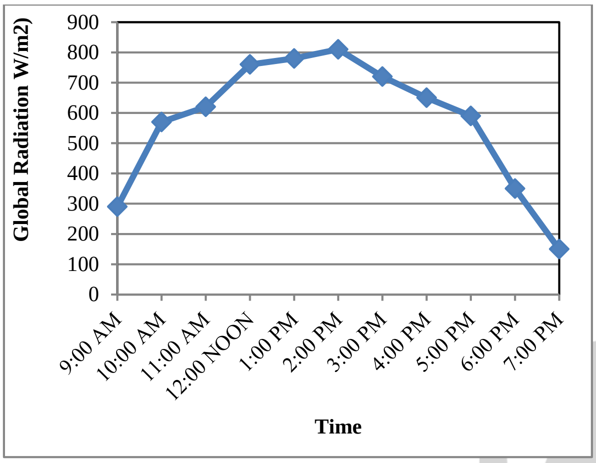

Figure 6 Global radiations on Solar Still with respect to time

Figure 7 shows the variation of distilled water output from the solar still with respect to time with and without PCM in the pipe. The graphs are plotted for 4 cm of water level in the solar still. The quantity of water coming out of the solar still is slowly increasing and at 12:00 noon, the outlet flow of water is 40 ml/s without PCM in the pipe. Whereas, with PCM in the pipe, at 12:00 noon, the water outlet is 60 ml/s. Then, the increase in water outlet is at a rapid rate, and it reaches a maximum value of 200 ml/s at 2:00 p.m. similarly, the water outlet is 260 ml/s at 2:00 pm for the PCM in the pipe. After 2:00 pm, the water coming out of the solar still is decresing and it reaches a value of 20 ml/s without PCM in the pipe and 50 ml/s with PCM in the pipe. It is construed from the figure that there is an increase in water output from 30 ml to 60 ml per second from the solar still with the use of PCM in the pipe compared to without PCM in the pipe.

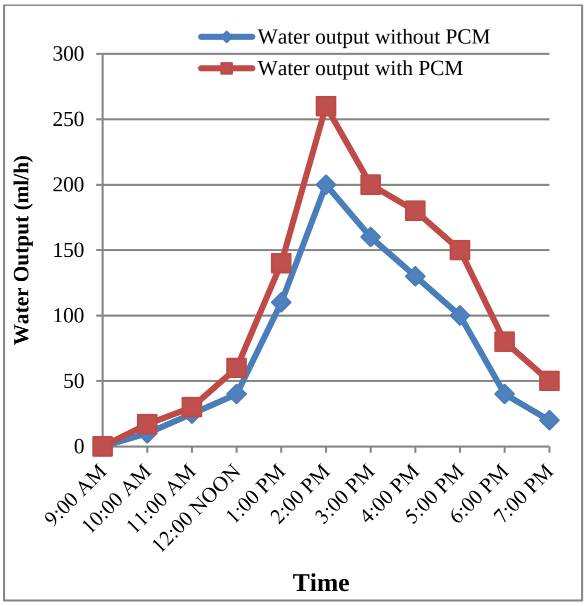

Figure 7 Variation of distilled water output from solar still with respect to time with and without PCM in the pipe

Figure 8 shows the efficiency of the solar still with and without PCM in the pipe. It is seen from the figure that the efficiency gradually increases, and at 2:00 p.m., it reaches a maximum value of 62% and 55% for with and without PCM in the pipe. The efficiecy slowly decreases until 4:00 p.m. At 4:00 p.m. the efficiency is 59% and 53% for with and without PCM in the pipe. Thereafter, the decrease in the PCM is at a faster rate, and at 7:00 p.m., the efficiency is 3.2% and 1.8% for with and without PCM in the pipe, respectively. It is seen from the figure that there is a 5-7 % increase in the efficiency of solar stills with PCM in the pipe compared to those without PCM in the pipe. It is construed that the efficiency of a solar still with PCM in the pipe is better than that of a solar still without PCM in the pipe.

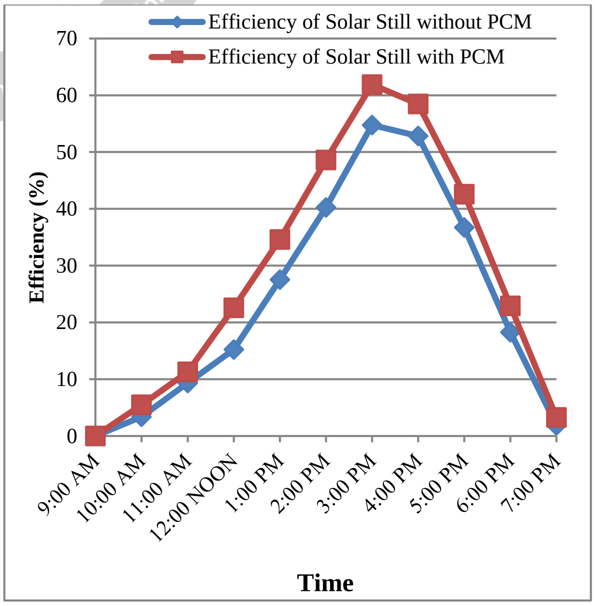

Figure 8 Variation of efficiency of solar still with respect to time for with and without PCM in the Pipe

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IV. CONCLUSION

PCM-incorporated pipe is connected to the solar still. The PCM-incorporated pipe is heated by solar radiation, and PCM stores latent heat energy and gives heat energy to water to raise its sensible heat while flowing through the pipe. The purpose of this work is to evaluate the increase in productivity of the solar still by using phase change material (PCM) as a storage medium. Based on the experiment conducted and the discussion carried out, the following conclusions are drawn:

- The use of PCM as storage material in the pipe reveals an increased distilled water output of about 5% with a 4 cm water level in a solar still.
- The efficiency of a solar still with and without PCM is found to be 27% and 20% respectively.
- The optimal water level for both types of solar stills is found to be 5cm.

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