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Research Article

Energetic and Exergetic Performance of PCM Incorporated ETC Integrated Solar Still under Forced Mode

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Abstract: The incorporation of phase change material (PCM) enhances the productivity of the solar still as well as makes it continuously operative during low sunshine/night time. This study analyzes the performance of single slope solar still incorporated with paraffin wax as a PCM beneath the basin liner and further integrated with an evacuated tube collector under forced convection. The results have revealed that under similar climatic conditions, PCM-incorporated solar still improves the productivity by 30% compared to the system without PCM, yielding 5.064 kg/day using 15 kg PCM at 0.03 m water depth and flow rate of 0.06 kg/s. The overall energetic and exergetic efficiencies have been found to be 39.56% and 4.05%. Irreversibility has been seen as a function of the intensity of available radiations during the daytime and is crucial at basin liner and, minimum at PCM. Moreover, at night, basin water has the highest irreversibility of ~78% (~30.0 W/m^2), while PCM is at a minimum of ~2.0 W/m^2. The effect of wind velocity has revealed an increase in energy efficiency by ~3%, reaching a maximum of 44.03% at an optimal speed of 3.0 m/s, while exergy efficiency decreased by ~11%. The increase in PCM and basin water mass has reduced the performance, reaching a maximum of 15 kg paraffin wax for a given water depth.

Keywords: Active solar still, Phase change material, Energy, Exergy, Irreversibility

1.Introduction

Worldwide scarcity of fresh water has been increasing, and it is expected that scarcity may reach 1.7–2.4 billion global urban people in 2050 [1]. A person needs a minimum of 20-50 liter/day of fresh water for the necessary usage, and about 700 million were facing scarcity, with nearly half in sub-Saharan Africa in 2014 [2]. About 13 × 107 m^3 of daily potable water is produced globally using conventional fuels to meet the potable water scarcity [3]. Moreover, such a productive quantity of potable water is insufficient to meet the requirements of the remote area, and scarcity has emerged as a crucial concern worldwide. To lower the use of fossil fuels and to meet potable water scarcity, applying the decentralized desalination plant by utilizing renewable energy, particularly solar, is a viable option. Access to uncontaminated water is paramount to uplift living and health standards. Solar still is an attractive option and is feasible for operating at affordable cost in remote areas with scarcity of potable water.

Nevertheless, the low yield and inconsistent productivity during off-sunshine hours are the main drawbacks of passive solar still. Much research has been carried out to increase the performance of solar stills by incorporating various modifications, which in turn led to enhancing the yield [4]. Incorporating energy storage materials (sensible and latent heat) has been found to further augment the performance of passive and active modifications of solar stills [5-7]. Moreover, incorporating latent heat storage material with a solar still system has been reported as more advantageous than sensible heat storage due to its higher energy storage density of phase change materials (PCM), and their effects have been reviewed [8]. About 67% higher yields were reported by incorporating PCM with conventional solar still [9]. The daytime yield decreases with the increased mass of PCM, and the night yield increases as the mass of the PCM increases. It was reported that the optimal performance of PCM to basin water mass is 1:2 [10]. Among these PCMs, paraffin wax possesses the most desirable properties but is associated with low thermal conductivity [8].

The general comparative performance criteria of different designs of solar stills under various climatic conditions is energy efficiency. Energy efficiency is based on the first law of thermodynamics, and due to limitations, it does not account for the irreversibility of various parts of the system. An exergetic assessment of the thermal system has been an alternative approach to conducting a comparative qualitative assessment. Exergetic assessment predicts a system's thermal performance, provides a quantitative and qualitative evaluation of various energy distractions, and identifies the areas for improvement. A steady-state, transient exergetic theoretical assessment of passive solar still has revealed the basin liner, water, and solar still efficiency as 12.9%, 6.0%, and 5.0%, respectively, with maximum irreversibility of 2/3rd at basin liner [11]. An increase in exergy efficiency of up to 2 m/s wind velocity with an insignificant effect on glass tilt has been reported [12]. Moreover, limited energetic and exergetic assessments of solar still systems incorporated with PCMs have been reported. The exergetic assessment of PCM incorporated passive solar still reported and found the instantaneous exergy efficiency <5% during the day and > 80.0% at night in some cases [13-15].

To enhance the productivity of single slope solar still was integrated with parallel evacuated tubes collector (ETC) under natural mode and found the daily yield of 3.8 kg/m^2 with daily energy/exergy efficiencies as 33.0% and 2.5%, respectively, at optimal flow rate 0.06 kg/s for 0.03 m water depth and 10 tubes [16]. Further, incorporating 10 kg of paraffin wax underneath the basin yielded 20.32% higher than the system without PCM with maximum daytime energy and exergy efficiency of 17.93 and 6.95% [17]. Force mode integration permits better heat extraction and prevents the adverse effects of internal recirculation, stagnation temperature, and mixing hot and cold fluid. A decrease in energy efficiency of 10% by decreasing the flow rate from ~0.019 to 0.009 kg/m^2 with 60 parallel vacuum tubes has been reported [18]. The current research indicates a growing interest in solar collectors that integrate solar still with energy storage material. Therefore, a numerical simulation has been performed for single slope solar still incorporated with paraffin wax and coupled with parallel ETC tubes operating under the forced mode, not reported before. The energetic and exergetic assessment was conducted from the viewpoint of finding the viability of the modified geometry compared to the system operating without PCM under similar climatic conditions. Exergy analysis has also been carried out to evaluate the irreversibility of different components. The investigation also highlights the temperature, yield, energy, and exergy efficiency change with time.

2.System Description

A schematic of the proposed configuration of a single slope solar still with PCM and ETC integration is shown in Fig. 1. The solar still is made of 0.005 m thick FRP material with 15 kg paraffin wax between the basin liner and base connected with 10 numbers of evacuated tubes and still glass cover tilted at 15^o while ETC at 45^o. The pump circulates the water between solar still and ETC. Evacuated tubes of 1.4 m long are spaced at 0.07 m and have inner/outer diameters of 0.044 m and 0.047 m, respectively, with a diffuse. To absorb the maximum radiation, selective blackened absorber coating is provided on the outside surface of the inner glass tubes. Fractions of solar radiation are absorbed by respective parts of the system and get heated. The heated absorber liner passes the heat to basin water and PCM beneath during radiation availability. Basin water evaporates and condenses below the glass cover and is taken outside. During the non-availability of radiation, the basin water and liner temperature decrease, and the PCM starts discharging by reverse heat transfer to the liner until equilibrium is reached. The circulated water through ETC is heated at high temperatures and mixed with basin water to enhance the temperature and improve the difference between the water and the glass surface temperature. During off-sunshine hours, solar energy is still cut off from ETC by providing a check valve to prevent reverse flow.

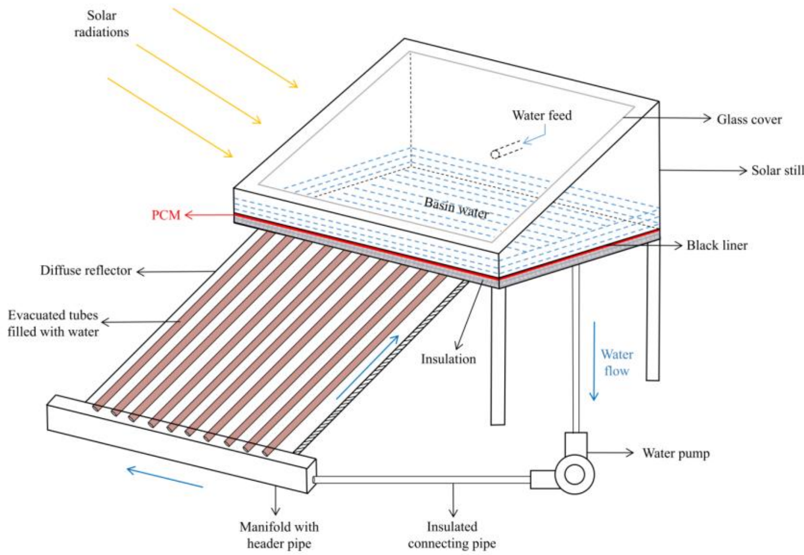

Figure 1: Schematic of PCM incorporated ETC coupled solar still.

3.Energetic and Exergetic Analysis

A general approach to estimating the performance of thermal systems is based on energy efficiency. However, because of certain limitations, the true approach is exergy-based (high-grade energy). A system may be more productive, but it does not mean that it has higher exergetic efficiencies. The instantaneous energy efficiency ($\eta_{i,o}$) of proposed solar still can be expressed as [14];

$$\eta_{i,o} = \frac{h_{ew}(T_{sw}-T_{gi})A_b}{[I_c\,(t).A_c.+I_s(t)A_g]} \times 100 \tag{1}$$

Where T_{sw}, T_{gi}, $I_c(t)$, I_s (t), A_c, A_g and h_{ew} are the basin water temperature, glass cover temperature, solar radiation on collector and solar still surface, area of glass cover, area of collector and evaporative heat transfer coefficient, respectively.

The Exergy associated with a thermal system for the energy transfer $'\dot{q}\,'$ can be estimated between the source (T_s) and sink (T_{amb}) can be represented as under [13];

$$\dot{E}x = \dot{q}\,\left(1 - \frac{T_{amb}}{T_s}\right) \tag{2}$$

The exergy efficiency (ε_k) is a measure of irreversibility and for component (k) of the solar still can be evaluated.

$$\varepsilon_k = 1 - \frac{\dot{I}_k}{Ex_{in,k}} \quad (3)$$

Exergy component corresponding to energy transfer in various part of the solar still can be written as;

(i) solar exergy input $(\dot{E}x_{in,S})$ on the integrated system can be expressed as;

$$\dot{E}x_{in,S} = 0.933\left[I_s\,(\mathrm{t})\,A_g + I_c(t)A_c\right] \quad (4)$$

(ii) exergy of basin $(\alpha_b'\,\dot{E}x_{sun})$, basin water $(\dot{E}x_{bw})$, PCM transfer $(\dot{E}x_{bp})$, transfer to ambient $(\dot{E}x_{pa})$ and the remaining gets destroyed $(\dot{I}_b)$. The irreversibility $(\dot{I})$. of thermal component can be estimated using following general equation (5);

$$\dot{I} = \dot{E}x_{in} + \dot{E}x_{gen} - \dot{E}x_{acc} - \dot{E}x_{out} \quad (5)$$

Where $\dot{E}x_{gen}$ and $\dot{E}x_{acc}$ are the exergy generated and exergy accumulated in the component, k. The energy balance equations of proposed ETSS-PCM at various locations, the temperatures at inner glass cover (T_{gi}), outer glass cover (T_{go}), basin liner (T_b), basin water (T_{sw}), ETC outlet (T_{cw}), PCM during charging (T_{pcm}), basin ($T_{b,d}$) and water temperatures ($T_{sw,d}$) during the discharging can be estimated by combining and solving the various energy/exergy balance equations at the components [8, 13, 14]. Moreover, the equations are not repeated here for the sake of brevity.

4.Results and Discussion

A numerical analysis has been carried out for the modified configuration by solving energy and exergy balance equations for the climatic conditions of Delhi, as reported [16]. The variation of temperatures at various components of solar still estimated with and without PCM for the typical summer day of May 2008 incorporating 15 kg PCM, 0.03 cm water depth, 10 ETC tubes, and 0.06 kg/s flow rate are shown in Fig. 2.

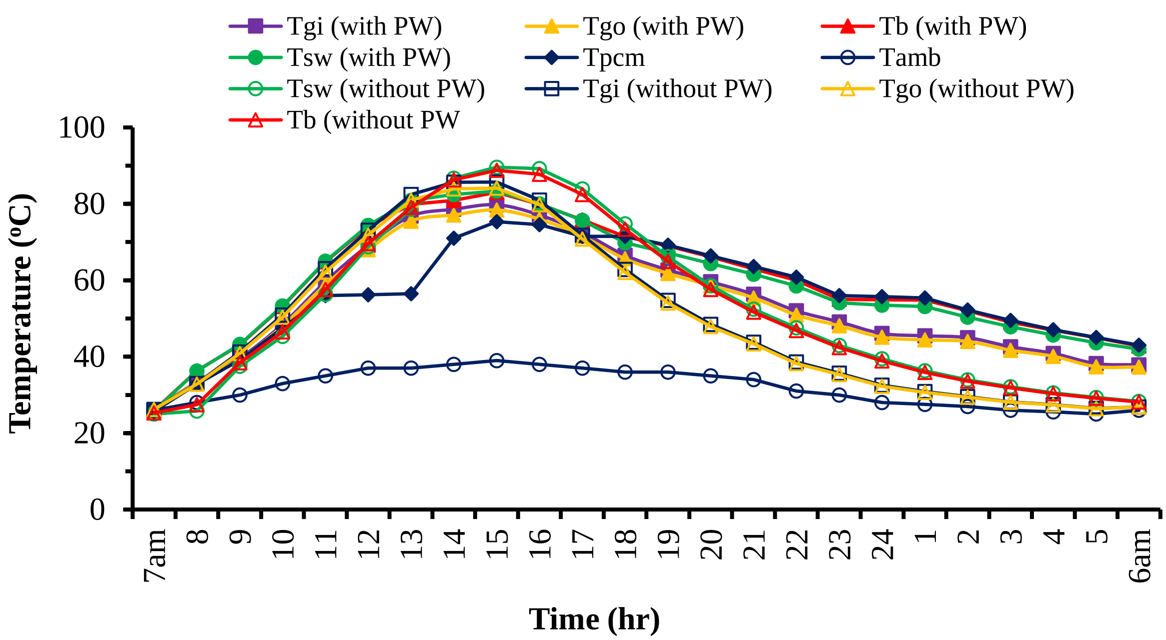

Figure 2: Variation of temperature with and without PCM.

The maximum water, basin, glass, and ambient temperatures are observed at 1500 hrs, and then decreased further and in accordance with the results expected. The maximum respective water and basin temperatures of 83.4 and 83^{o}C are seen from the solar still with PCM, and typically lower ~5.0^{o}C than the system without PCM, due to the way PCM works to absorb and store heat. During the early hours, PCM temperature gradually increases, changes its phase, and further increases, reaching a maximum around 3 PM. At night, the basin and water temperatures are higher in the range of ~1.6-49.5% than the system without paraffin wax. This is due to the supply of storage energy of PCM to the basin and water during the period of low radiation availability and at night.

Fig. 3 depicts the variation of overall instant energy and exergy efficiencies of a solar still with PCM. The instantaneous energetic and exergetic efficiencies are influenced by the factor accounting operational and climatic parameters together [$(T_{wo}-T_{amb})/I_s$ (t)] while keeping the other parameters fixed. The slope of the characteristic curves is positive due to temperature-dependent physical properties of the heat transfer coefficient, and energy and exergy efficiencies increase with the increase in parameter [12]. The instant energy and exergy efficiencies of the system with PCM are lower during the daytime compared to the system without PCM. The instantaneous exergy efficiency is found to be lower in range (0.0-16.8%) compared to the energy efficiency (0.0-141.2 %) because of irreversibility associated with various components of the system. The high value of energy efficiency over 100% during evening time is due to the low solar intensity used as a denominator term.

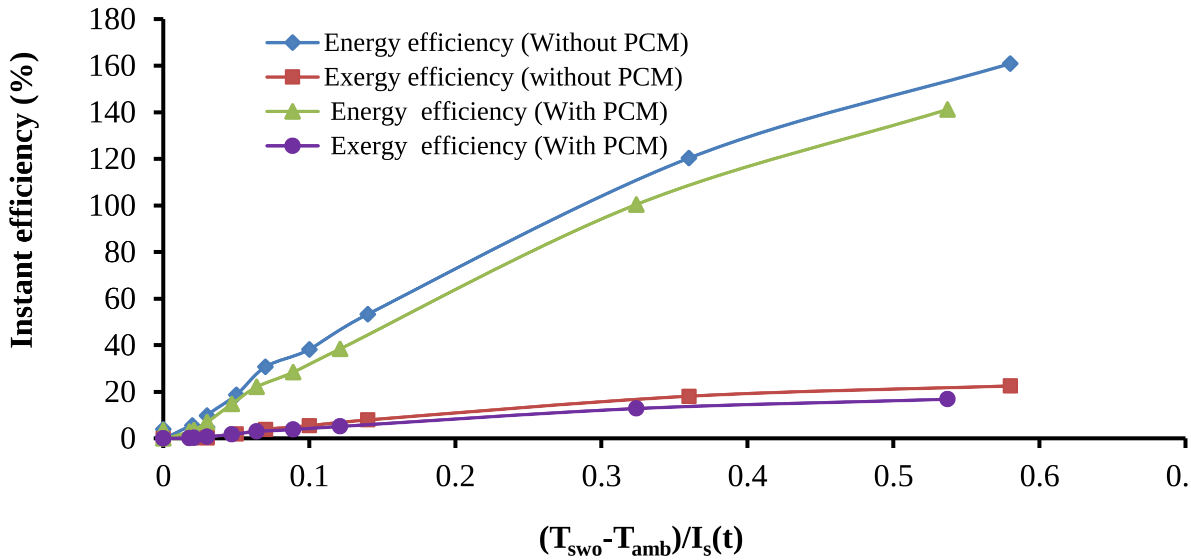

Figure 3: Characteristic curve for instant energy and exergy efficiency.

Irreversibility, which is based on the entropy criterion, affects the productivity of solar still. This effect can be identified by studying the exergy destruction associated with evaluating the exergy efficiency and quantifying the suggestive improvement in design. Fig. 4 shows the irreversibility at various components, and it has been found to be higher during the sunshine than during the off-sunshine period. The maximum irreversibility is reached at peak time availability of the radiation and confirms the results reported. The lowest irreversibility occurs at the PCM layer (20 W/m^2) and maximum at the basin liner (260 W/m^2), possibly due to the blackened liner, which allows low heat transfer to basin water. The irreversibility in the basin liner decreases the exergy efficiency significantly. The irreversibility of the glass cover occurred at 80 W/m^2. During the night, basin water contributes about 80% irreversibility owing to the energy it receives from PCM. The increase in irreversibility occurs with an increase in PCM thickness during the day and night.

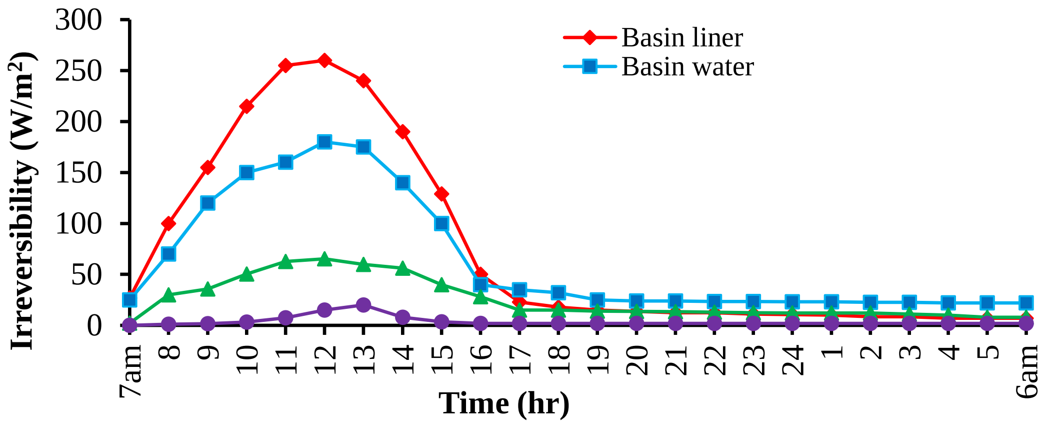

Figure 4: Irreversibility at various components of solar still.

The exergy efficiency of modified geometry is a measure of how effectively it converts available solar energy into useful products. The incorporation of PCM plays a significant impact on exergy efficiency, and its thickness plays a crucial role. Fig. 5 depicts the effect of paraffin mass (PCM) on energy and exergy efficiency. The higher the thickness, the more energy is stored in PCM, maintaining a consistent temperature profile in basin water and higher yield during the night with decreased exergy losses, which are associated with low PCM mass. Too thick PCM decreases the performance, as stored heat may not be available when the solar still requires it most and increases irreversibility in both sunshine and night periods. Overall performance improved at optimal PCM thickness due to minimized exergy destruction by maintaining a better energy balance between storage and heat transfer.

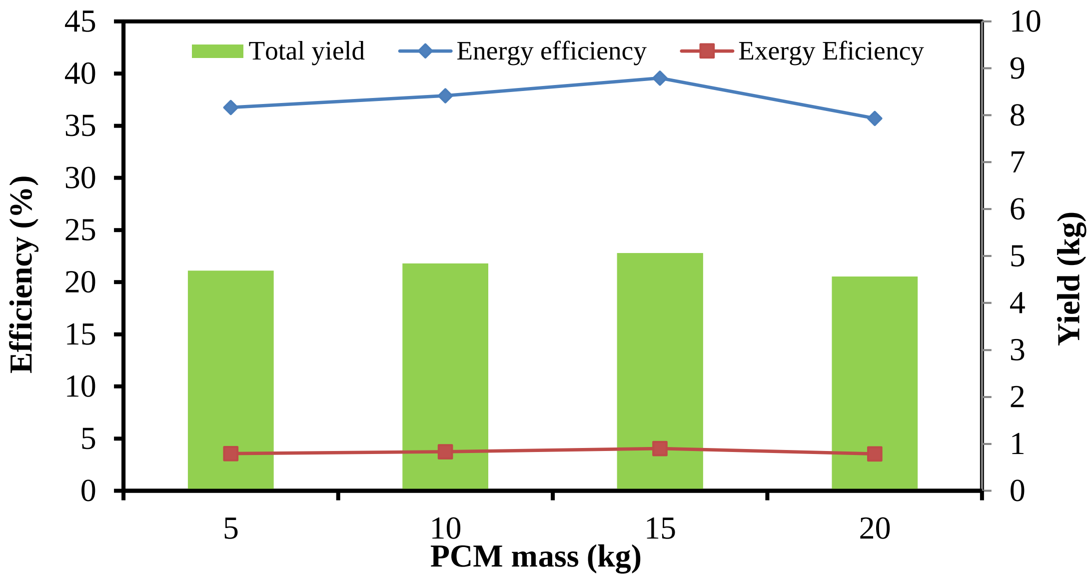

Figure 5: Effect of PCM mass on system performance.

The very low wind speeds may cause stagnation, leading to a loss of PCM effectiveness in the lower basin water mass. Therefore, an optimal wind speed required estimation to achieve the highest efficiency of the present geometry. Fig. 6 shows the effect of wind velocity on solar still's energetic and exergetic performance for the wind speed ranging 1-5 m/s, 0.03 m water depth, and moderate PCM mass of 15 kg, reported optimum. With the increase in wind speed from 1-3 m/s, energy and exergy efficiency enhanced by ~2.7%, reaching a maximum of 3 m/s. With the further increase in wind velocity, performance insignificantly decreases. This is due to the increased temperature difference between basin water and the inner glass cover surface, leading to increased evaporation. The increase in convective heat transfer from the basin water with an increase in wind speed results in a decrease in water temperature after a critical value of wind speed. With lower wind speed, PCM can store more energy and discharge it when required, enhancing efficiency. An increase in wind speed increases the entropy generation and reduces exergy efficiency due to a reduction in temperature difference between basin water and ambient, thereby decreasing the exergy for PCM. The decrease in exergy efficiency from 3.95 to 3.38 % is evaluated with an increase in wind speed from 1 to 5 m/s. The increase in wind speed from 1 to 3 m/s has revealed an increase in energy efficiency by ~3.0%, reaching a maximum of 44.03%, while exergy efficiency decreased by ~11%.

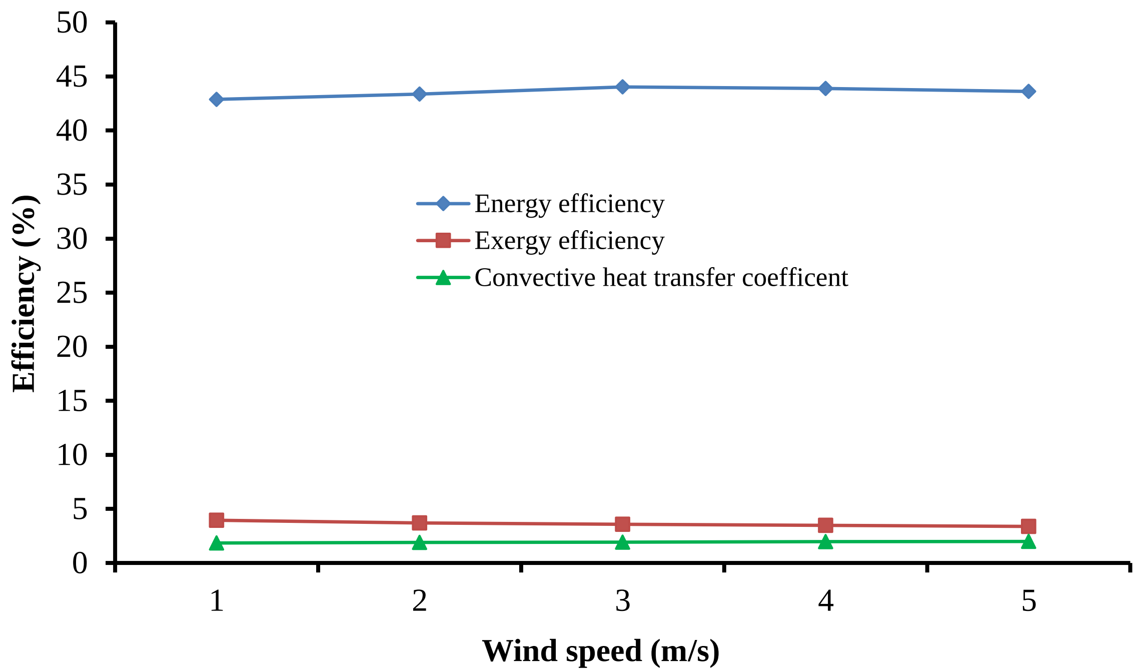

Figure 6: Effect of wind speed on performance.

With the increase in water depth, PCM is able to store more energy and work more effectively during sunshine periods, leading to higher exergy efficiency and better overall performance during the night. Moreover, a low water depth leads to higher water temperature and faster evaporation during the day. An optimal water depth balances the factors to achieve the highest performance of a PCM-incorporated ETC-integrated solar still, as shown in Fig. 7. The maximum overall daily energy and exergy efficiency has been found at lower water depth, typically at 0.02 m, with energy and exergy efficiencies at 40.36% and 4.5%, respectively. The optimal water depth of ETC-integrated solar still without PCM has been reported as 0.03 m [14].

The comparative performance of ETC integrated solar still under forced mode with and without PCM is shown in Fig. 8. For similar climatic conditions and water depth of 0.03 m and 15 kg PCM, the overall yield, energy efficiency, and exergy efficiency are found to be increased by ~30%, 17%, and 79%, respectively, compared to the system without PCM.

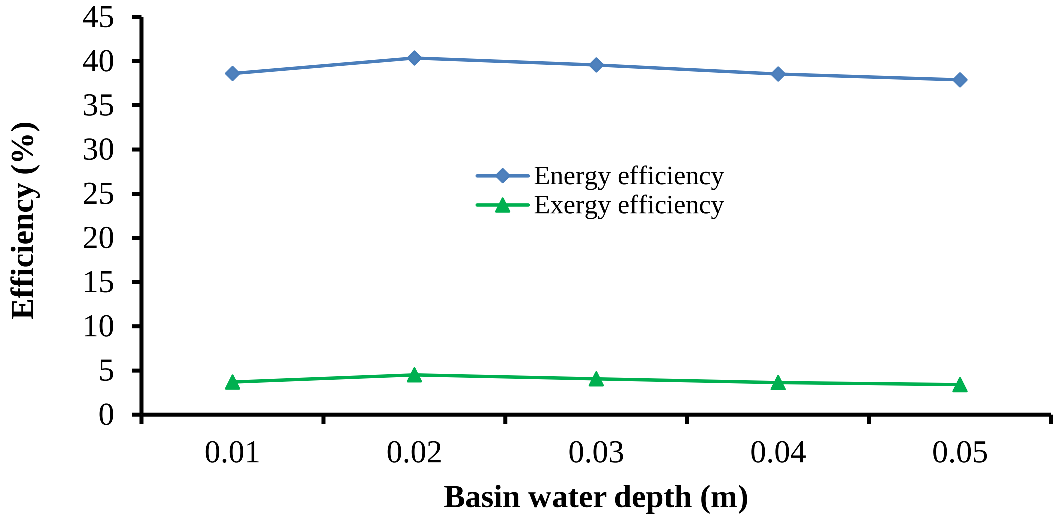

Figure 7: Effect of water depth on the performance.

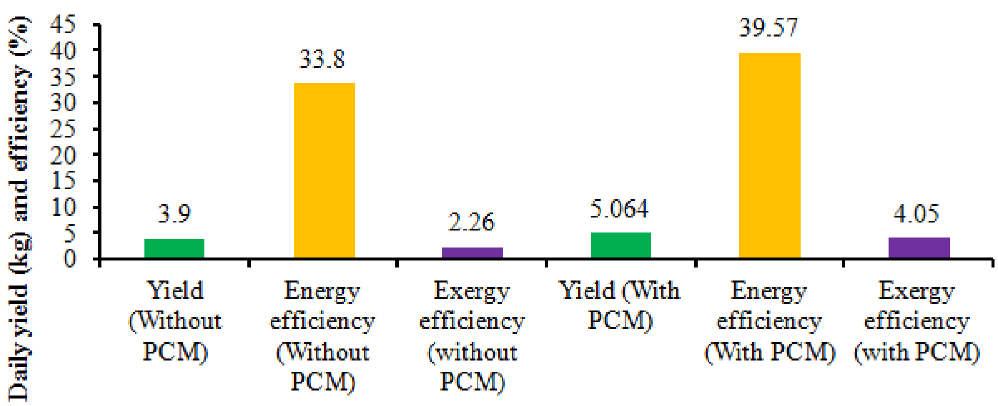

Figure 8: Comparative performance of solar still with and without PCM.

5.Conclusion

From the analytic analysis of ETC integrated solar still incorporated with PCM operating under forced mode, the following conclusions are drawn;

(a) On a typical day in summer, daily yield, energy, and exergy efficiency are higher by ~30%, ~17%, and ~79%, respectively, compared to the solar still without PCM.

(b) Irreversibility has been seen as a function of the intensity of available radiations. Higher irreversibility is found at basin liner during the day while at PCM minimum.

During the night, maximum irreversibility is found at basin water, maintaining a minimum trend at the PCM layer.

(c) The crucial wind speed of 3 m/s is estimated from the energy and exergy efficiency viewpoint. The effect of wind velocity has revealed an increase in energy efficiency by ~3%, reaching a maximum of 44.03% at an optimal speed of 3.0 m/s, while exergy efficiency decreased by ~11%.

(d) With the increase in water mass, higher values of energetic and exergetic efficiency are found at 0.02 m water depth.

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