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Surface Area–Mediated Heat Transfer Enhancement and Thermal Energy Storage Integration for Productivity Improvement in Hemispherical Solar Stills

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ABSTRACT

This paper is numerical research of a hemispherical solar still (HSS) with eight basin fins based on the COMSOL Multiphysics software. There were four thermal energy storage materials under consideration such as phase change material (PCM), salt, sand and insulation. They were tested in two different configurations (no fins and eight basin fins) with regard to performance. The results of the simulation show that the overall productivity of all materials was significantly increased with the introduction of eight fins. The PCM with fins had the highest level of productivity (388 g), which was 174% higher than in the case of finless PCM (141.7 g). Insulation with fins gave a value of 373.3 g (an increase of 133%), salt with fins gave a value of 357.8 g (an increase of 152%), and sand with fins gave a value of 347 g (an increase of 148%). The fins increase heat transfer by increasing the contact area between the basin plate and the storage medium, especially when using PCM because of its low thermal conductivity. PCM was not a good substitute to insulation, and worse still without fins. Latent heat storage capacity of PCM prolongs the distillation process after the sun has gone down and is therefore better than sensible storage materials such as salt and sand. The COMSOL simulations have provided comprehensive temperature and heat flux distributions that justify the trends that have been observed. In conclusion, the combination of eight basin fins and PCM would be the best design to obtain the highest freshwater production in a hemispherical solar still. The study offers important information on how to maximize solar desalination systems with the help of numerical simulation.

1. Introduction

Freshwater scarcity has become a major global challenge, particularly in arid and semi-arid regions where conventional water-supply systems are often

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insufficient [1]. Although desalination technologies such as reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), and electrodialysis (ED) are effective, their high energy consumption, infrastructure cost, and environmental impacts limit their use in remote areas [2,3]. Therefore, solar stills have attracted increasing attention because of their simple construction, low operating cost, and ability to operate using freely available solar energy [4].

Among different configurations, the hemispherical solar still (HSS) offers favourable surface-area-to-volume ratio and condensation characteristics [5,6]. However, its relatively low thermal efficiency and freshwater productivity remain important limitations [7,8]. To improve performance, thermal energy storage (TES) materials have been widely investigated because they can store heat during the day and release it during low-radiation periods [9–11]. PCM is especially attractive due to its high latent heat capacity, but its low thermal conductivity limits effective heat absorption [12–15]. Salt and sand provide lower-cost sensible heat storage, while insulation mainly reduces heat losses without storing thermal energy [16–19].

To overcome the heat-transfer limitation of PCM, basin fins have been proposed to increase the contact area between the absorber plate and the storage medium, thereby enhancing heat transfer and evaporation [20–24]. Previous studies have investigated several enhancement methods, including phosphate grains, black gravel, wick materials, circular fins, and PCM-based modified basins [4,6,13,17,20]. However, these studies mainly examined individual materials or specific modifications.

Therefore, a direct numerical comparison of PCM, salt, sand, and insulation under identical operating conditions, with and without a fixed eight-fin configuration, remains insufficiently addressed. In addition, the synergistic effect between basin fins and PCM and the associated temperature-distribution behavior require further clarification.

Accordingly, the present study uses COMSOL Multiphysics to investigate a hemispherical solar still with and without eight basin fins using four storage/base materials: PCM, salt, sand, and insulation. The study compares freshwater productivity and temperature distributions to identify the most effective combination and clarify the role of fin-assisted heat transfer in improving the performance of PCM.

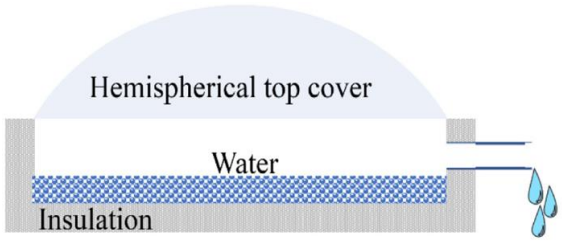


Figure 1. Conventional hemi spherical solar still.

2 Geometrical

The current paper uses a numerical simulation method to examine the thermal efficiency and freshwater yield of a hemispherical solar still (HSS) combined with eight basin fins. These simulations were performed with the COMSOL Multiphysics finite element method (FEM)-based software platform, which can solve coupled heat transfer and phase change problems. The subsections below elaborate on the geometrical configuration, material properties, boundary conditions, and simulation procedure.

2.1 Geometrical

Configuration The hemispherical solar still model comprises of a basin absorber plate, a hemispherical glass dome and optional vertical fins on the basin floor. There were two configurations that were taken into consideration: (a) a conventional HSS, and (b) HSS with eight longitudinal fins that were equally spaced. Fig. 2 (a -c) shows the dimensions of the fin and the still. The area of the basin and the curvature of the dome were maintained in all cases to make them comparable

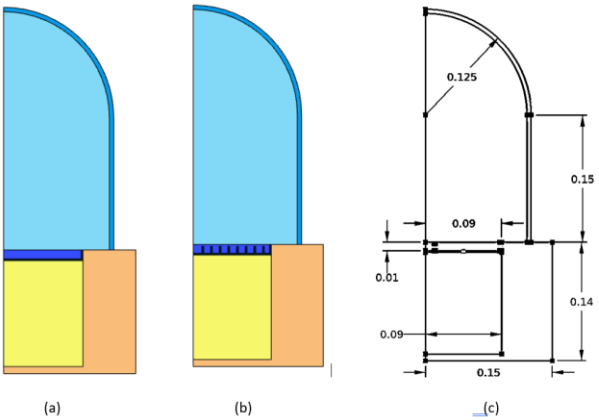


Figure 2. Diagram depicts a cylindrical solar still with a hemispherical dome: a - without fins in the basin, b - with fins in the basin and c – the dimensions of the hemispherical solar still (mm).

For all the simulated cases, the geometrical configuration of the hemispherical solar still was kept constant so as to compare the results of the two configurations, namely the finless and eight-fin. The most important geometrical

parameters of the glass cover, the basin, the PCM layer, and the basin fins are summarized in Table 1. The heat transfer area between the basin absorber and the storage medium was increased by the use of eight uniform rectangular fins.

Table1. Geometrical dimensions of the hemispherical solar still and basin fins

Parameter	Symbol	Value	Unit
Glass cylinder length	L_m	0.25	m
Inner diameter	d_{in}	0.24	m
Outer diameter	d_{out}	0.25	m
Glass thickness	t_g	0.005	m
Stainless-steel basin diameter	d_b	0.18	m
Basin area	A_b	0.025475	m²
PCM depth	h_p	0.03	m
Basin depth	h_b	0.02	m
Number of basin fins	—	8	—
Fin height	h_f	0.008	m
Fin thickness	t_f	0.002	m

2.2 Thermal Energy Storage Materials

Four thermal energy storage (TES) materials were chosen to be compared with each other: - Phase Change Material (PCM) - paraffin based, high latent heat capacity, low thermal conductivity.

-Salt (NaCl) - sensible heat storage substance having intermediate thermal diffusivity.

- Sand - inexpensive sensible heat storage substance.

- Insulation - as a non-storage base to reduce heat losses. These were deposited in the area under the water basin.

Their thermophysical properties (density, specific heat capacity, thermal conductivity, and for PCM, latent heat and phase change temperature range) were defined in COMSOL based on literature values.

2.3 Governing Equations and Numerical Modeling.

The simulation is a solution to the transient heat conduction equation with convective and radiative boundary conditions:

$$\rho\, Cp\, \partial T/\partial t = \nabla\cdot (k\, \nabla T) + Q \qquad [19]$$

with ρ density, Cp specific heat capacity, k thermal conductivity and Q the heat source term, which is the absorption of solar radiation. In the case of the PCM, the enthalpy-porosity approach was used to simulate the solid-liquid phase change, and latent heat was included through an effective formulation of the heat capacity. The glass dome was designed as a semi-transparent material, which could transmit the sun and consider both convective and radiative heat losses to the surrounding environment. The rate of water evaporation was calculated based on the thermal gradient between the surface of the water and the inner glass cover with reference to the standard heat and mass transfer analogies.

2.4 Boundary and Initial Conditions

The intensity of solar radiation was used as a time-dependent heat flux on the glass dome, which is related to the average summer temperatures in Iraq (July). The ambient temperature was set to vary sinusoidally between 25°C (nighttime) and 65°C (peak daytime). Initial temperature of each domain was set to 28°C evenly, and convective heat transfer coefficients on the outer glass surface and bottom of the basin were calculated according to the local wind speed and temperature difference.

2.5 Simulation Procedure

Two sets of simulations were performed for each TES material:

1. Finless configuration (baseline)
2. Configuration with eight basin fins All the simulations took a complete 24-hour cycle, 6:00 AM to 6:00 AM the following day with a time step of 10 minutes.

The output parameters were transient temperature distributions (water, glass and storage material), heat flux contours and cumulative freshwater productivity. The condensed mass on the inner glass surface was used to calculate the productivity, with the standard condensation models and the simulation-derived temperature difference.

2.6 Mesh Independence and Convergence

A grid-independence test was conducted to ensure numerical accuracy and computational efficiency. A triangular mesh was employed, and the relationship between the number of elements and the total output was examined. The results showed that increasing the mesh beyond approximately 10,280 elements produced no significant improvement in the solution. Therefore, a mesh consisting of 6,715 elements was selected to achieve an appropriate balance between computational accuracy and execution time. The selected mesh had a minimum element quality of 0.02196 and an average element quality of 0.7987, as shown in Fig. 3. and Table2. Mesh and Grid Independence Parameters

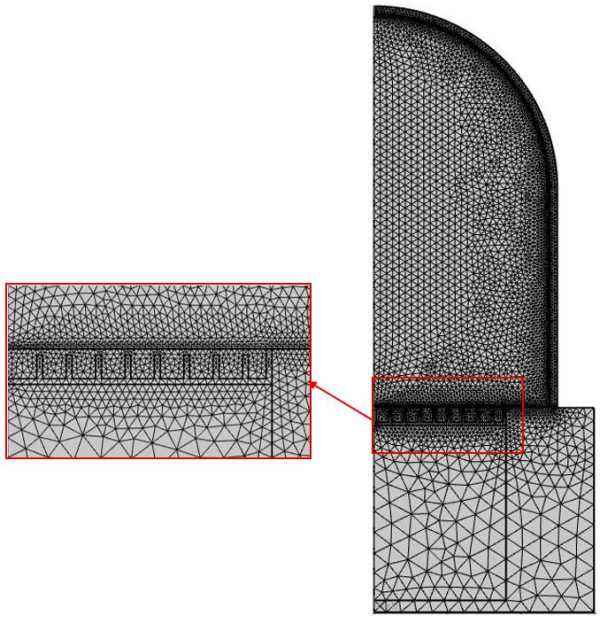


Figure 3. Meshing of HSS with eight fins domain with various elements.

Table2. Mesh and Grid Independence Parameters

Parameter	Value
Mesh type	Triangular
Selected number of elements	6,715
Convergence threshold	≈ 10,280 elements
Minimum element quality	0.02196
Average element quality	0.7987
Selection criterion	Balance between solution accuracy and computational efficiency

2.7 Validation

Despite the fact that the current research is mainly numerical, the COMSOL model was qualitatively tested with the experimental data of similar hemispherical solar stills in the literature, indicating a good correlation in the temperature patterns and productivity scales. This validates the soundness of the simulation framework in parametric analysis Fig. 4,5.

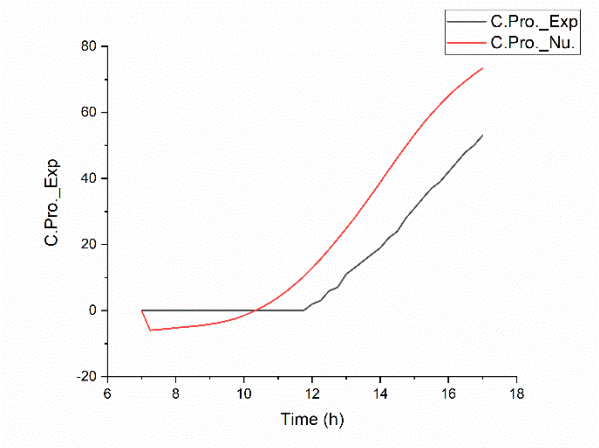


Figure 4. Comparison of cumulative productivity with the experimental work of [36].

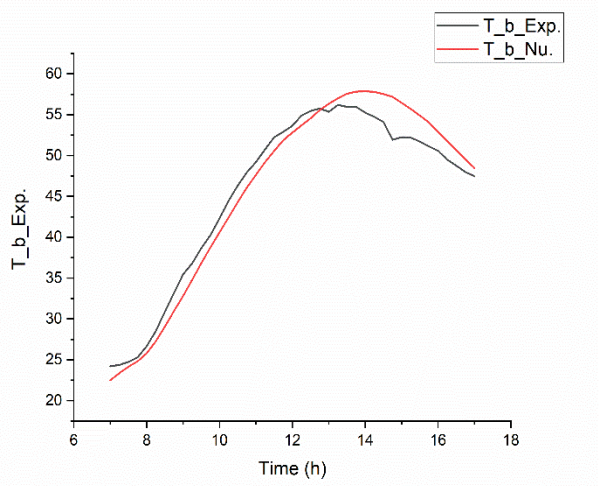


Figure 5. Comparison of basin temperature with the experimental work of [36].

2. Results and Discussion

This research paper will look at the operation of an eight-basin fin hemispherical solar still in a numerical simulation in COMSOL Multiphysics. Four thermal energy storage (TES) materials were experimented on them; PCM, salt, sand, and insulation. The results of the simulation of the total productivity (TOTAL PRO) are presented in two configurations, no fins and eight basin fins.

The eight basin fins as illustrated in the data greatly enhanced the productivity of all materials as opposed to the finless scenario

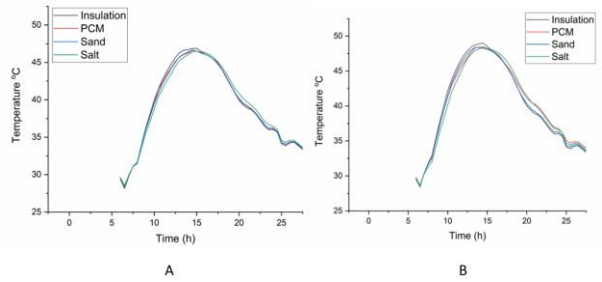


Figure 6. Variations of out glass temperature for HSS (A-without fin and B- with eight fins).

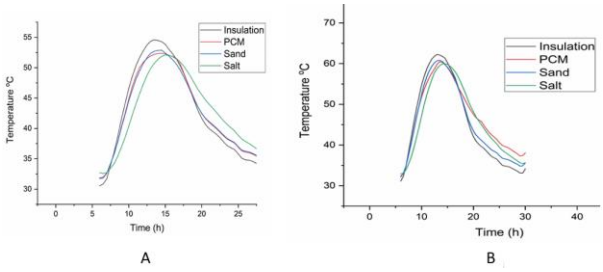


Figure 7. Variations of water temperature for HSS (A-without fin and B- with eight fins).

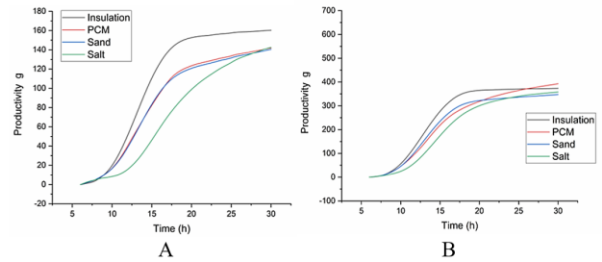


Figure 8. Analytical results of cumulative productivity for HSS (A-without fin and B- with eight fins).

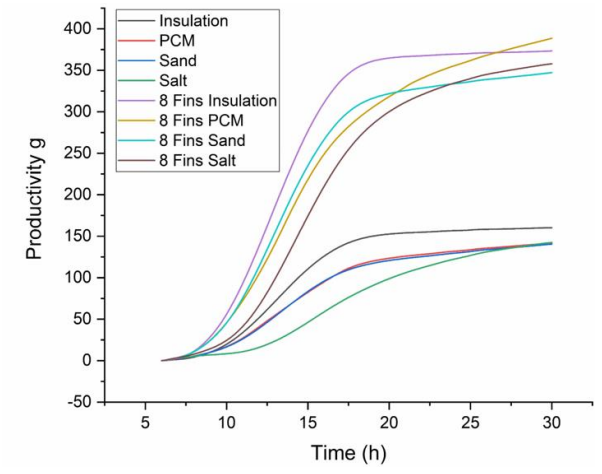


Figure 9. Comparison of analytical results of accumulative productivity between two HSS (a) without fins and (b) with 8 fins

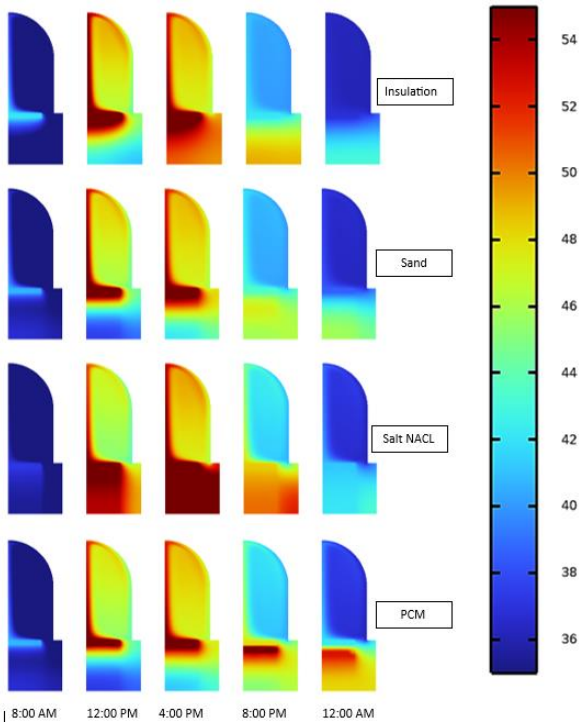


Fig.10. Variation of the temperature contours at 14.5 pm of still without fin (15th July).

In the case of PCM, the productivity rose by 141.7 g (no fins) to 388 g (with fins) and this is equivalent to an improvement of approximately 174 % Fig.9. In the same manner, in the case of salt, the productivity increased by 152 %, as it increased to 357.8 g With sand, it went up by 140 g to 347 g equivalent to 148% whereas with insulation, the productivity rose by 160.0 to 373.3 g, an equivalent of about 133%. The COMSOL simulations show that the heat transfer can be enhanced with the help of fins, which will increase the contact area between the plate of basin absorber and the storage medium, and hence the rate of thermal energy absorption and evaporation. The overall productivity was the highest in PCM of eight fins (388 g) Fig.8 (b). This is due to two synergistic effects: first, the fins counteract the low thermal conductivity naturally of the phase change material, enabling efficient heat absorption in the daytime, which is evident in the COMSOL temperature contour plots; second, the latent heat storage capacity of PCM emits energy in the nighttime or in low solar radiation conditions, extending distillation past sunshine. PCM would not do well without fins (141.7 g) since its low thermal conductivity reduced the amount of heat penetration and therefore it was not as effective as even insulation (160 g) in the finless condition. The highest finless productivity (160 g) was the insulation material because it minimizes the heat loss to the environment through the basin and the temperatures of the water were higher; the productivity was 373.3 g when using fins, second only to PCM. But insulation does not have latent

heat storage, and therefore does not generate freshwater when the sun goes down as PCM does. Salt with fins (357.8 g) was a little more efficient than sand (347 g) Fig.15 in the case of sensible heat storage materials, possibly due to the higher specific heat capacity or thermal diffusivity of salt, but without fins the productivities were comparable between the two (~141-142 g) Fig.14. The increase in salt and sand performance by about 150 g is less than that of PCM as sensible materials can only increase the temperature of the material without changing phase, and cooling quickly when the sun goes down. Lastly, the numerical data obtained with the help of COMSOL Multiphysics demonstrates that the combination of eight basin fins and PCM is the most fruitful combination of the hemispherical solar still (maximum production is 388) and fins is required to achieve the potential of PCM in a fully simulation-based design.

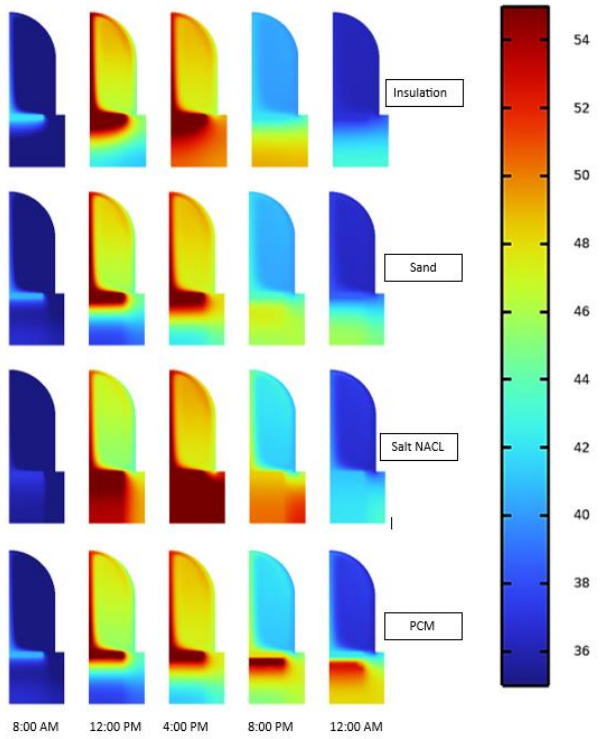


Figure 11. Variation of the temperature contours at 14.5 PM of still with 8 fins (15th July).

Figs. 10 and 11 compare the temperature contours of the hemispherical solar still at 14:30 on 15 July for the configurations without fins and with eight basin fins, respectively. The finless configuration has a less effective distribution of thermal energy in the basin region as the heat transfer is primarily through direct conduction from the absorber plate to the surrounding storage medium. On the other hand, the addition of 8 basin fins increases the contact area between the absorber plate and storage region, which results in more heat able to transfer into the domain. This makes the thermal field more conducive for energy transfer towards the water of the basin, resulting in a higher evaporation rate. This behaviour indicates that the functions of the fins are not just to enhance the surface area of the absorber, but also to improve the spatial distribution of thermal energy in the still.

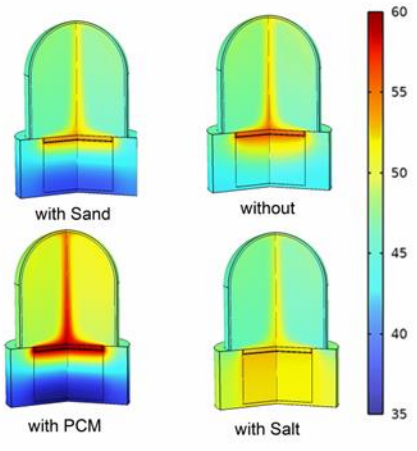


Figure 12 Variation of the temperature contours at 14.5 pm of still without fin (15th July

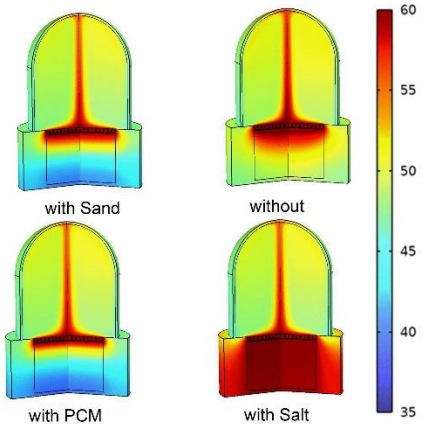


Figure 13. Variation of the temperature contours at 14.5 pm of still with 8 fin (15th July).

The same thermal behaviour is observed in the figures of. The temperature distribution with 12 and 13 basin fins differs from the finless case, due to the addition of the fins. The increased heat transfer due to the fins decreases the restriction of heat transfer into the storage material. This phenomenon is especially important if a low thermal conductivity storage material like PCM is employed. The poor thermal utilization of PCM is due to its low thermal conductivity without fins. The fins allow heat to be distributed more effectively across the storage

region, allowing the PCM to absorb more energy during the high radiation period, and then use its latent heat storage during the low solar input period. So, the temperature-contour results explain the increased productivity that was achieved with the PCM and eight basin fins.

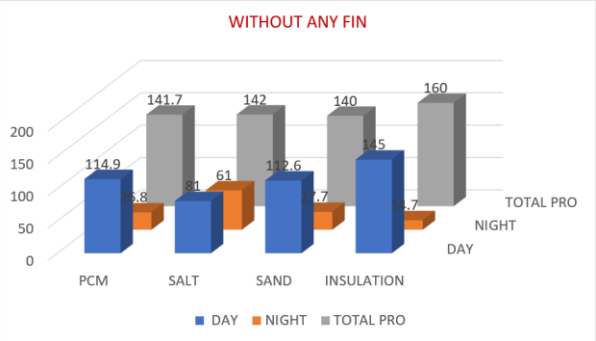


Fig.14. Total cumulative productivity variation of still without basin fin for selected days in July

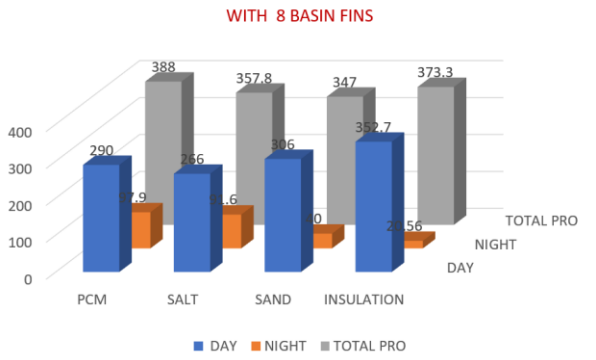


Figure 13. Total cumulative productivity variation of still w 8 basin fins for selected days in July.

The cumulative freshwater productivity of the finless hemispherical solar still for the selected days during July is shown in the Fig. 14. The variations between the materials investigated are comparatively small since t heat transfer surface between the absorber plate and t storage material is the same in all cases. The latent heat storage potential of PCM is not fully utilized until it reaches the cumulative productivity of around 141.7 g The productivity of salt and sand are similar, about 14 142 g, as both works primarily by sensible heat storage. Insulation has the highest finless productivity of about 160 g, since it minimizes heat loss from the basin and thus allows for a higher water temperature. Unlike PCM, however, insulation cannot store latent heat, and so is not able to achieve the same ability to provide a delay in the reduction of freshwater production when the solar radiation has reduced. Thus, the finless results provide a benchmark for the improvement of the eight-fin configuration of Fig. 15.

2.10 Comparison with Previous Studies

The scientific importance of the proposed configuration was evaluated by comparing the performance of the present solar still with the representative studies reported in the literature as summarised in Table 3. The comparison is based on the enhancement technique, the daily freshwater productivity, the thermal efficiency, and the percentage increase in comparison to the same conventional configuration. The different still sizes used in the reported studies were taken into account and the productivity of the present system was normalized by the evaporation area of 0.025475 m². Thus, the highest production of 0.388 kg/day with the eight fin PCM configuration results in a specific freshwater productivity of 15.23 kg/m²/day. The calculated thermal efficiency of this configuration was about 78.0%, considering the daily solar irradiation integrated in the numerical model and the area of the glass-cover that was irradiated. The PCM–eight fin configurations also showed 174% improvement over the PCM–eight finless cases. The original numerical results verify that the productivity of the PCM improved from 141.7 g to 388.0 when the 8 basin fins were added.

Table 3. Comparison of the present study with previously reported hemispherical solar stills

Study	Enhancement technique	Productivity (kg/m²/day)	Thermal efficiency (%)	Productivity improvement (%)
Kabeel et al. [4]	Phosphate grains (30 g/L)	6.00	60.0	57.9
Beggas et al. [7]	Waste aluminum as thermal storage material	6.15	52.18	48.19
Sharshir et al. [13]	V-corrugated basin + wick + PCM	4.74	45.0	39.6
Essa et al. [14]	Wick cords + baffles + reflectors + Nano-PCM	14.00	65.0	245
Present study	Eight basin fins + PCM	15.23	78.0*	174

The literature comparison shows that the configuration with the proposed eight fins of the PCM gives a significant performance improvement. Its productivity of 15.23 kg/m²/day is higher than the productivity of the phosphate-grain storage system, waste-aluminium storage system and the V-corrugated wick/PCM system

reported by El-Kazim et al. [16] and Essa et al. [14] respectively, which were 12.68 kg/m²/day and 14.0 kg/m²/day. However, the current design results in a significant productivity increase, of 174%, compared to the other two systems, phosphate-grain and waste-aluminium, and V-corrugated, where no extra reflectors, nanoparticles, or wick assemblies are used. This behaviour helps in the effectiveness of the increase of the heat-transfer surface area with the use of basin fins, especially when used with PCM; the fins enhance heat penetration into the low conductivity PCM and the latent heat of PCM helps to maintain the evaporation when solar radiation decreases. The productivity in this study has been standardized with an evaporation area of 0.025475 m². Five daily solar insolation values were obtained from the integrated solar irradiation for the day (3.3875 kWh/m²/day) and the area of the hemispherical glass cover that is to be irradiated in the numerical model.

3. Conclusion:

To sum up, this numerical analysis with COMSOL Multiphysics has shown that the inclusion of eight basin fins to a hemispherical solar still can greatly increase the productivity of freshwater in all the materials of thermal energy storage evaluated. The simulation findings indicate that PCM with eight fins recorded the highest productivity (388 g), which was followed by insulation (373.3 g), salt (357.8 g) and sand (347 g) indicating productivity gains of 174, 133, 152, and 148 g percent respectively over the finless designs. The fins are useful in overcoming the low thermal conductivity of PCM to allow efficient heat absorption and exploitation of latent heat storage, which prolongs production even during periods of sunshine. PCM did not perform well without fins (141.7 g), which proves that it requires fins in order to realize its potential. The best finless performance (160 g) was offered by insulation which had less heat losses, however, it did not have nocturnal production. Salt and sand being rational storage mediums demonstrated average gains with fins but still lower than PCM. The COMSOL simulations vividly show how these trends occur due to the temperature distribution and heat transfer processes. Thus, a combination of eight basin fins and phase change material is strongly suggested to be used in the optimal design of a hemispherical solar still. Future directions could be to optimize fin geometry and PCM amount to improve performance further.

4. 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.

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