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Modeling and simulation of a helical-finned tube integrated with paraffin wax in a solar water heater system for enhanced thermal energy storage performance

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ABSTRACT

Flat-plate solar water heaters are widely used due to their ease of use and acceptable performance relative to their cost. However, the novelty of this work lies in studying numerical simulations using computational fluid dynamics for the integration of helical half-fins into a phase-change material, placed on the back side of the absorber tube surface of a flat-plate solar water heater. The finite-volume method was used to analyze the phase-change material's transition time from liquid to molten state. Calculations for both (Ra ≈ 2.3×10^3) and (Ste ≈ 0.19) revealed the true behavior of latent heat transfer during the phase-change material's melting. Numerical analysis showed a 9.33% increase in the average liquid content in the helical half-fin model from 2:00 PM to 8:00 PM, indicating that the paraffin melting rate is faster in this model compared to the paraffin-only model. In addition, the temperatures of the water exiting the three samples at midnight were 300.37 K, 302.043 K, and 304.36 K, respectively. These results confirm that the improved thermal performance of the solar water heater is due to the integration of both paraffin wax and spiral fins, which that accelerates the melting process, and thus improves thermal energy storage

Keywords: solar collector, solar energy, PCM, helical fins, thermal energy sorage. CFD, heat transfer.

INTRODUCTION

The shift to renewable energy sources has become an inevitable reality to compensate for the depletion and high cost of traditional fossil fuels, their environmental impact, and the increasing demand for energy driven by global development. Solar energy is among the most promising renewable energy sources due to its sustainable availability and environmental friendliness. Flat-plate solar water heaters (FPSWHs)are the most common and widely used solar energy systems in residential and industrial applications because of their ease of manufacture, reasonable cost, and low maintenance requirements (Mustafa and Karima, 2016) [1]. However, the efficiency of traditional (FPSWHs) is limited due to the irregular and intermittent nature of solar radiation, as well as the difficulty in continuously storing water heat in the absence of sunlight. Jafar et al. (2017) [2] also conducted a numerical study of a modified flat-plate solar water heater with twisted plates and helical springs within the solar collector's lifting tubes. They recorded performance improvements of 10% and 6.8% respectively.

Phase change materials (PCMs) are among the most suitable solutions for storing latent thermal energy, due to their high storage density. These materials have gained significant traction as thermal energy storage applications. During the melting process of PCMs in the presence of solar radiation, latent heat is stored in the PCMs through charging a process, this heat is then recovered during solidification process (discharge) after abcence solar radiation, This is cousing the stabilizing of the heated water temperature and increasing its utilization of solar thermal energy even after peak solar radiation periods (Abdelnabi et al., 2018; Fadzlin et al., 2022) [3,4]. The use of annular fins are the further improves transient heat transfer and influences energy storage in heat exchanger (Hasan and Suffer, 2024) [5]. They also possess the ability to maintain a nearly stable temperature during melting/solidification processes (Cabeza et al., 2006; Benchara et al., 2020; Singh and Sagar, 2019) [6,7,8]. (Selimefendigil and Oztop, 2026) [9] studied the effect of zegzag fins shape on the performance of a PCM thermal storage system. They are emploied the numerical simulations using finite element method. The analysis were carried out by using zigzag fins integratted with PCM during the melting process under forced convection. They found that the melting time decreased by 38.8% for the lowest flow rate ratio and by 43.4% for the highest flow rate ratio for both flat and zigzag fins.

Several studies have investigated on the possibility of integrating PCMs with solar thermal energy systems to improve their thermal energy storage performance. To achieving notable improvements in heat transfer rates (Suffer, et al., 2020) [10] they are investigate numerically the storage of solar energy in PCM (paraffin wax) in water solar collector. The numerical simulation was carried out using CFD technique the distribution of the temperature with the time for proposed water solar system. Enthalpy and Finite volume methods are conducted in their simulation. They are founded that the PCM is capable to storage the solar energy during day and discharge this energy at the night to in give peter performance to the water solar energy system. (Khalaf and Tojun, 2026) [11] focused on improving the heat storage performance of a shell-and-tube heat exchanger integrated with PCMs (paraffin wax). Numerical simulaton based three-dimensional models and applying enthalpy and porosity methods are conducted for nine different models, over a Reynolds number range (250–2000). The numerical simulation results showed that the time required for the melting of paraffin wax was significantly reduced in cases of presence of fins. The best reducing in time achieving 53.7% for the configuration of ree-curved fin configuration compared to the base finless configuration. Numerical studies have also investigated the effect of mixing nanoparticle on PCM performance. (Ebtihal and Ihsan, 2025) [12], conducted a numerical simulation using CFD technique to improve the performance of the solar energy system of for energy storage propose by mixing different concentrations of Alumina nanoparticles (Al_2O_3)with paraffin wax as a phase change material. 12%-11.76% improvement in the system are achiefd during the charging process and a 15.71%-19.60% during the discharging process. Yazdanparast et al. (2026) [13] improving the thermal performance of a rectangula chamber have a fins, filled with a deualPCM (combination of paraffin wax and lauric acid). They are examined both the melting and solidification caces with various fin configurations. The effects of varying the number of fins, the chamber's tilt angle, and the dimensions of both the chamber and fins are considered. Results of thier study provide valuable insights into the potential for improving the thermal performance of solar thermal systems integrated with phase-change materials. According to (Jabbar et al., 2025) [14] An experimental study was conducted to evaluate the performance of a thermal storage tank in a solar water heating system. The tank was designed as a tube-and-shell tank with 97 annular fins surrounding the tube. Experiments were carried out on three tanks: two filled with water and a phase-change material for latent heat storage, and the third filled with gravel for sensible heat storage. The results showed that the best heat storage was achieved with the phase-change material, at 0.87 kW/h, and with water, at 0.37 kW/h. The sensible storage with gravel was 0.1 kW/h. Their steady recorded that using PCM very effecient to storage solar thmal energy. Hassan and Suffer (2023) [15] designed a heat exchanger with pin fins welded to the outside tube surface, the ends these winded with a spiral wire. Both fins and wire were immersed in a phase change material PCM. They reducing the melting time and achieving an approximately 37.5% improvement in thermal response due to the increased contact area and improved temperature distribution within the PCM. Mohammad et al. (2023) [16] successfully integrated phase-change materials with a porous medium in a vacuum tube solar collector for thermal energy storage. They achieved a 50% increase in solar collector efficiency compared to conventional designs. Furthermore (Ali et al., 2025) [17], using CFD simulations, demonstrated that the shape of the fins influence the heat transfer behavior during the melting process of the phase-change materials. Therefore, the proposal concluded that improving the thermal storage performance of solar water heating systems enhances reliance on renewable energy and supports sustainability programs, highlighting the importance of renewable energy field.

The conventional FPSWHs are made up of parallel tubes with metal plates constituting the absorber surface that absorbs the solar radiation. The cross-section view for one tube shows that the extanded area on both tube sides, are suposed as a longitudinal fins. In the present study, longitudinal fins have been used as the baseline heat transfer enhancement method because of its geometrical and thermal similarity to the traditional FPSWHs. In this steady, numerical simulation will be carried out for one tube to minimize the complexity of computations and optimize the available memory resources and accurately represent the effects of heat transfers and flow. Three modles will be studied in this simulation, The first model is the baseline case Tube with longitudinal fins (TLF), the second model (TLF-PCM) is the baseline case integrated PCM (Paraffin wax) full in container under the baseline case arrangment for the propose of solar thermal energy sotrage. The third model (TLF-PCM-HHF), is half-metal helical fins wlded with the tube in the second model, then immeresed inside the PCM to enhance the heat transfer btween fluid flowing inside the tube and PCM, for the peopose of reduce the required time for melting of PCM. The primary objective for this simulation is to improve energy storing capability of a flat plate solar collector through combination of PCM and half-metal helical fin, which enhances the heat transfer to PCM, decreases time to fully melt the PCM and the overall thermal performance.This work addresses a gap in the literature by combining helical fin enhancement with PCM storage in a single-tube FPSWH configuration and providing detailed CFD analysis of the melting process. The novelty of this study lies in the combined use of PCM and half-metal helical fins within solar collector tubes, which has not been systematically investigated previously (Abdunnabi et al., 2018; Singh and Sagar, 2019; Suffer et al., 2020; Ahmed et al., 2021; Shukla et al., 2013; Patel, 2023) [3,8,10,19–21].

MODELING OF THE PHYSICAL MODEL AND COMPUTATIONAL DOMAIN

In the current work, numerical simulations will be conducted three-dimensional proposed models for one tube separated from solar water collector to comparison and to obtain the best results for improving the performance of a solar water heating system. Due to the large size of the real models and the difficulty of conducting numerical simulations due to the limitation of the computer processing memory, the model will be adopted for one tube of a conventional solar water heater. The three-dimensional models are modelled using SOLIDWORK 2021 software, the first model is (Tube with Longitudinal Fins, (TLF)) Figure 1a. The tube with Longitudinal fins have 990 mm long, and (10.025 mm, 12.025 mm) inside and outside diameter respectvily, then the necessary modifications will be made to the other two models: one is TFF model covered from the bottom by (990 × 101.56 × 11 mm) container filled with a PCM, (TLF-PCM), Figure 1b, and the other model is added (10) of a half-helical fin along the tube from the PCM side. The extended to the outside fin length is 4.5 mm, with a distance 100 mm between each fin (TLF-PCM+Half Helical Fins, (TLF-PCM-HHF)), Figure 1c. Figure 2 shows the cross sections for the proposed modals. The PCM used n this work is the Paraffin wax with the thermal properties that are tabulated in Table 1.

In this work, modeling of the three proposed models are curreid out using SOLIDWORK 2019 software in 3-dimensions. In order to achieve the best results with high accuracy, it is necessary

Table 1. Physical properties and mass of the paraffin wax

Discribtion	Value
Melting temperature range (K)	321–335
Heat of fusion (J/kg(	114540
Specific heat (J/kg·K)	2000
Viscosity coefficient (kg/(m·s))	0.033
Conductivity (W/m·K)	0.14
Density (kg/m^3)	820
Thermal expansion coefficient (1/K)	6×10^{-4}

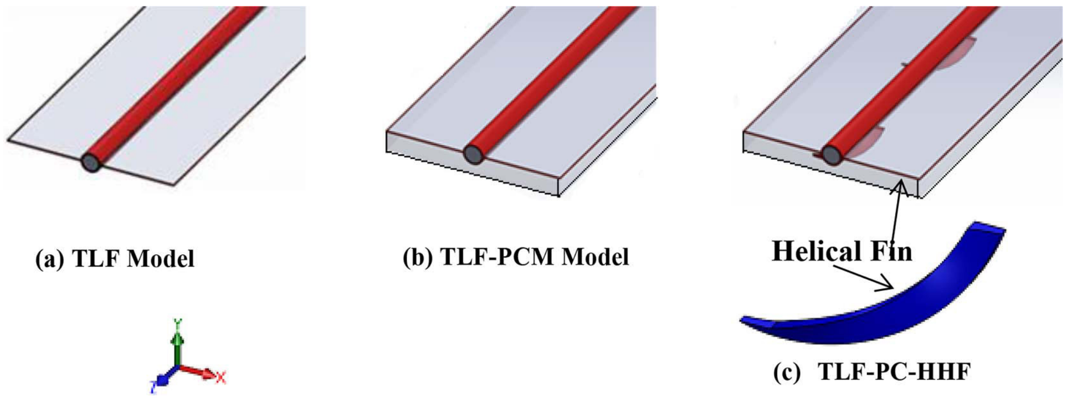


Figure 1. Modelling of one tube of a conventional solar water heater for three under current study cases

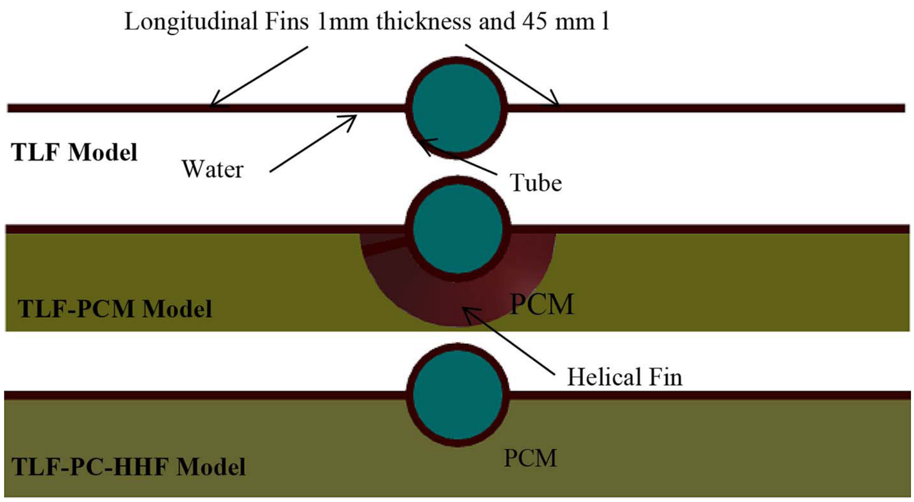


Figure 2. Cross sections in the three models: (a) TLF (b) TLF-PCM (c) TLF-PCM-HHF

to build the mesh for the TLF-PC-HHF model which is selected as a more geometry complex than the other two models TLF and TLF-PCM respectively. A grid dependent where different element sizes were tested. Figure 4 (a and b) shows the Tetrahedral shape of mesh is chosen for two models TLF and TLF-PCM respectively, while for the best results for the liquid fraction is selected in terms of accuracy and the computational cost, the total number of elements is (592291, 4123587, and 3254145) for TLF-PC-HHF model as shown in Figures 3, 4 (c). To get best results from the numerical simulation, Tetrahedral shape of mesh is chosen, as presented in Figure 2. Also, another study on time step sensitivity for different values, 60 seconds are used for the time step, and the maximum iteration is fix to 20 times btween each time step. The used PCM is soposed to be in solid phase in the processe starting (time is 0 s), and 293 K is the temperature of the PCM. The actual solar heat flux is taking as an actual from test in Baghdad city, and represented by un equation and making a curve fitting to this equation, then inserting in the pre-processing of this simulation depending on the time and supposed as a constant heat flux for all the solar water collector surface.

METHODOLOGY

Governing equations: With the development of modern technology, it has become a possible to rely on the use CFD technical tools to simulate applications if heat transfer and fluid flow problems, which focus on solving the Neverstock equations in each of the continuity, momentum, and energy form. Ansys Fluent is one of the promising software in solving the above equations and gives very acceptable results. The continuity equation (mass conservation) was adopted in this work, as stated in (Dincer, 1999) [22],

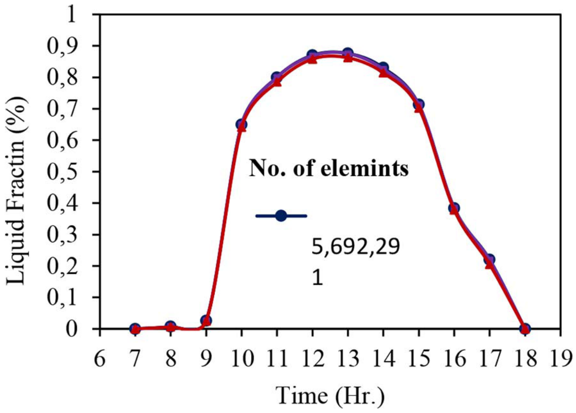


Figure 3. Liquid fraction variation with the hourly time for different number of elements

which usally used in simulation of thermal energy storage.

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{V}\right) = 0 \tag{1}$$

where: t is the time (s), $\vec{V}$ (m/s) velocity and ρ (kg/m^3) density of the PCM.

The momentum equation, adopted from (Reedy, 2007) [23], describes the motion of fluids during the melting of a phase change material resulting from buoyancy forces.

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \left(\nabla.\vec{V}\right)\vec{V}\right) = \\ = -\nabla P + \mu\left(\nabla^2 \vec{V}\right) + \rho g \tag{2}$$

where: P *(Pa)* pressure, μ *(Pa.s)* dynamic viscocity, and g (m/s^2) gravitational acceleration vector.

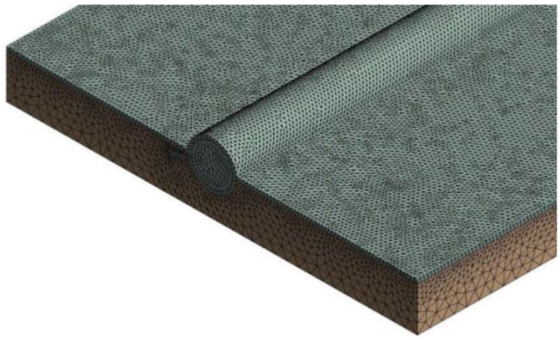
The energy equation, as presented in (El Qamia H., 2009) [24], was adopted. This equation considers heat transfer by both conduction and convection, as well as the latent heat associated with the phase change of a phase-change material.

$$\rho Cp \frac{\partial T}{\partial t} + \nabla \mathrm{T}.\left(\rho Cp\, \vec{V}\right) = \\ = k\nabla^2 T + \rho L_h \frac{\partial f}{\partial t} \tag{3}$$

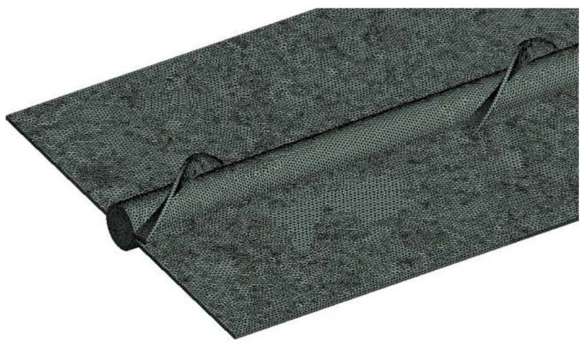
where: k (W/m.K) is the thermal conductivity, L_h (J/kg) latent heat of PCM, f liquid fraction (0 solid, 1 fully liquid).

(a) TLF Model

(b) TLF-PCM Model



(C) TLF-PC-HHF (side view)



C) TLF-PC-HHF (Bottom view for the helical fins)

Figure 4. Tetrahedral mesh of the three Models (TLF, TLF-PCM andTLF-PCM-HHF)

To understand the behavior of phase-change materials during melting, dimensionless equations for both the Rayleigh number (Ra) and the (Ste) Stefan number were considered Equations 4 and 5 in this simulation to determine the relative influence of natural convection and latent heat storage as stated in (Reedy, 2007; El Qarnia, 2009) [23,24] respective

$$Ra = \frac{g\beta(T_h - T_c)L^3}{\nu\alpha} \quad (4)$$

where: β (1/K) thermal expansion coefficient, (T_h&T_c) (K) hot and cool temperature, L (m) characteristic length, α (m^2/s) thermal diffusivity, and ν (m^2/s) kinematic viscosity.

$$Ste = \frac{Cp(T_h - T_m)}{L_h} \quad (5)$$

where: T_m (K) PCM melting temperature, L_h latent heat of fuion.

RESULTS AND DISCUSSION

To understand and evaluate the latent heat transfer behavior during the melting of the phase change material (PCM), Equations 4 and 5 are used to calculate both of Rayleigh and Stefan numbers based on the characteristic length of the PCM layer (0.011 m) and the temperature difference between the PCM and the absorber tube, as well as the thermophysical properties of the paraffin wax that are mentained in Table 1. Through simple mathematical calculations, the Rayleigh number was estimated to be Ra ≈ 2.3×10^3. This value indicates a weak onset of natural convection within the molten region of the PCM, with heat transfer primarily occurring by conduction. The Stefan number, also calculated to be (Ste≈0.19), it is noted that the latent heat of fusion plays a significant role in the process of thermal energy storage. From these results, we conclude that heat is stored primarily due to the phase change of the phase-changing material, with a moderate contribution from natural convection to heat transfer during the melting process.

Numerical simulations of water heating were carried out in the first model (TLF) of the proposed solar water heater, as well as the other two models with the addition of paraffin wax and helical fins (TLF-PCM, and TLF-PCM-HHF) to study the melting process of paraffin wax and its effect on water heating and improving the performance of the proposed solar water heater. After completing the numerical simulation process, several results were obtained for each of the liquid fraction with temperatures distribution, which will be discussed and presented following figures. Figure 5 represents the change in the paraffin liquid ratio over time for the two models (TLF-PCM and TLF-PCM-HHF). A value of 1 indicates a 100% liquid fraction, while a value of 0 indicates a zero liquid fraction, with the wax is completely solidified. Its observe that the liquid fraction increases with the increase in incident solar radiation during the first half of the day, reaching its maximum value at midday. At the time 1:00 PM, the maximum value of liquid fraction is 0.91 for the TLF-PCM-HHF model, and 0.874 for TLF-PCM model. The wax begins to solidify after this time and when the solar radiation decreases. When taking the average melting rate from 2:00 PM to 8:00 PM, Its noted that the liquid fraction is 9.33% higher (TLF-PCM-HHF) model than the (PCM-HHF) model. This suggests that the helical fins contributed to increased wax melting, thus improving the efficiency and performance of the solar water heater. It is clearly evident that the liquid fraction in TLF-PCM-HHF model is greater in the presence of fins, due to their effect on accelerating heat transfer compared to the TLF-PCM model.

Figures 6 and 7 show the contours of liquid fraction versus daylight hours for the TLF-PCM and TLF-PCM-HHF models. Three times were selected: the beginning, middle, and end of the day, representing the incidence of solar radiation. In addition, the contours of liquid fraction were

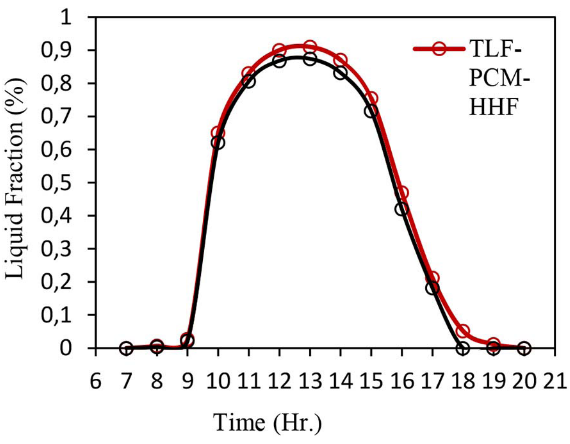


Figure 5. Liquid fraction versus daylight hours for the (TLF-PCM, and TLF-PCM-HHF) models

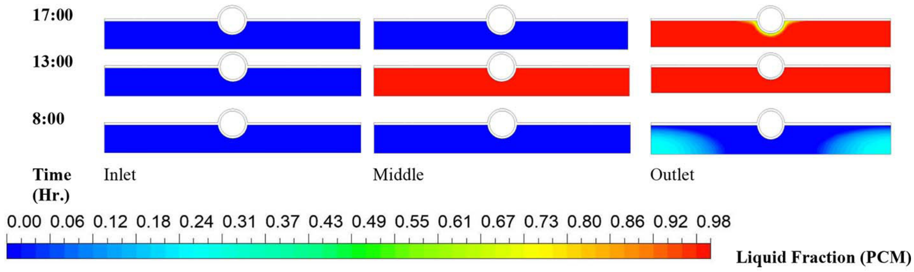


Figure 6. Liquid fraction versus daylight hours for the (TLF-PCM) models

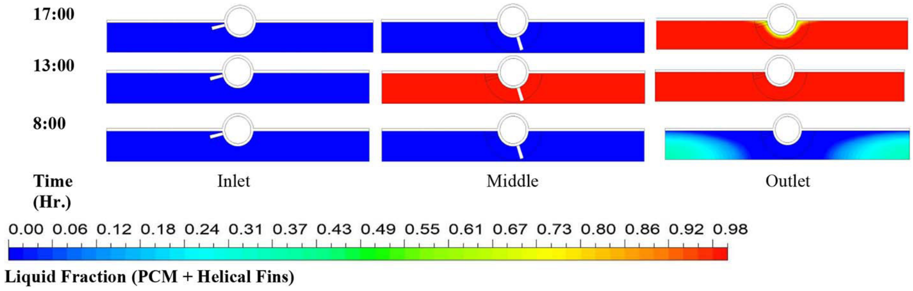


Figure 7. Liquid fraction versus daylight hours for the (TLF-PCM-HHF) model

presented in cross-section of the two models at three locations: at the beginning of water entry into the tube, in the middle of the tube, and at the end of water exit from the tube. Figure 8 shows the liquid fraction contours for the TLF-PCM-HHF model, located deep within the paraffin wax, in the direction of water flow along the model, and at different times of the day. It is clear from these contours that the liquid fraction of paraffin increases with increasing solar radiation incident on the model in the early hours of the day before noon, represented by the charging process of the wax, and decreases with decreasing radiation after midday, represented by the heat dissipation process from the wax to the water.

Figure 9 present the variation of outlet water temperature with the day time. From this figure, can notice that the water temperature increases with the increasing daylight hours, as represented by the increase in solar radiation during the day, reaching its highest temperature at midday, between 12 a.m. and 1 p.m. During the first half of the day, its notice that the temperature of the outside water in the tube model alone is slightly higher than in the other two models. This is attributed to the presence of PCM, which in turn draws heat away from the flowing water during the PCM charging process. While in the second half of the day, in the afternoon, clearly notice that the outside water temperature is higher in the case of the PCM for both (TLF-PCM, and TLF-PCM-HHF) models, and is more clearly higher in the TLF-PCM-HHF model, because heat transfer is faster with the presence of fins. After the disappearance of solar radiation, water heating stops at the time 5:00 p.m. in the TLF model, while it continues in the other two(TLF-PCM, and TLF-PCM-HHF) models because the heat stored in the PCM is released into the water during the discharge process, which increases until the time 10 pm to heat the water. From these results its observe that TLF-PCM-HHF model improves performance better than the TLF-PCM model, and both are superior to the TLF model. Its notice from the results of Figure 9, when taking the average temperature at the afternoon time to the end of the day for the three models that the average temperature of the water coming out, returns to the initial state at 4 pm is 300.37 K for (TLF) model, while it is at midnight are 302.043 K and 304.360 K in each of the other (TLF-PCM, and TLF-PCM-HHF) models that is because of contain paraffin wax.

Figures 10, 11, and 12 show the contours of temperature distribution daylight hours for the TLF, TLF-PCM and TLF-PCM-HHF models. Four times (8:00, 9:00, 13:00, and 17:00) were selected The contours of temperature distribution in these models were presented in cross-section at three locations: at the inlet, middle, and the outlet of the tube. From Figures 10, 11, and 12, also its

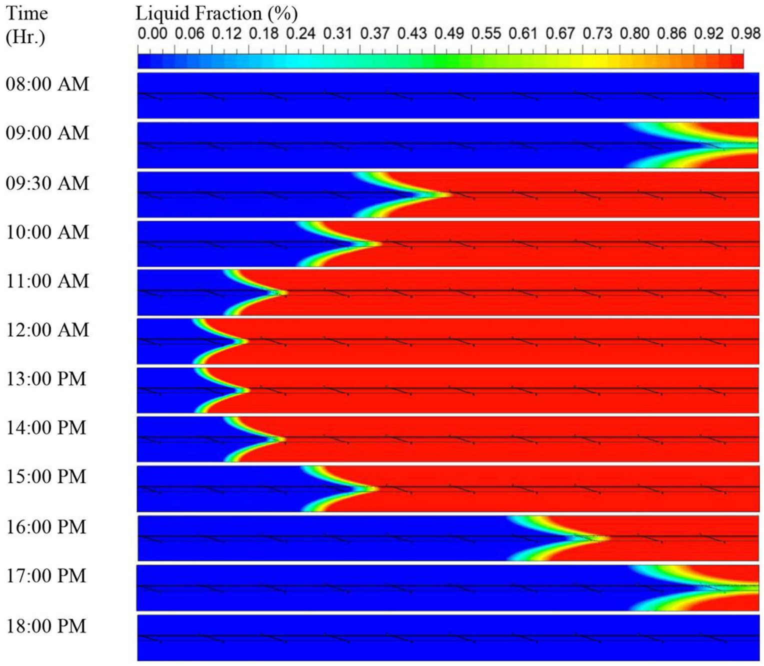


Figure 8. Liquid fraction versus daylight hours for the (TLF-PCM-HHF) model

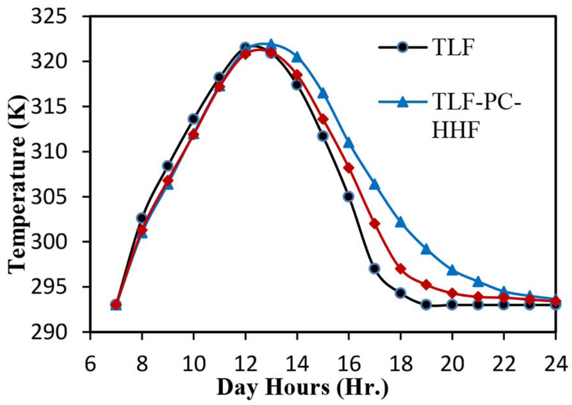


Figure 9. Outlet water temperature versus daylight hours for the (TLF, TLF-PCM, and TLF-PCM-HHF) models

observed that the temperature distribution in the three models is evident, represented by the zone of water flowing inside the tube, the two fins attached to the tube from both of right and left sides, and also in the container filling with PCM for storing the heat. Its observed from the results that the temperature of the water flowing inside the tube increases in the direction of flow. also note that the temperature spreads through the water from the outside to the center of the tube, as it is directed from the outer surface of the solar water heater. The temperature gradients of the water rise due to the increase in solar radiation during the first half of the day before noon, reaching the highest temperatures at the time of maximum solar radiation between 12:00 PM and 1:00 PM. The temperature then begins to decrease with the decrease in solar radiation. As for the (TLF-PCM and TLF-PCM-HHF) models containing wax, also note that the heat spreads from the outer surface of the solar water heater to the upper layers of the wax and continues toward the depth of the wax. These also follow the same pattern of increasing with the increase in solar radiation during the first half of the day, and the state of charge of the wax. After sunset and the cessation of solar radiation, the latent heat stored in the wax begins to be released, continuing to heat the water passing through the tube. This means the water will continue to be heated for a longer period of time until midnight, when the water temperature reaches its initial temperature. The concluded from the above results that the presence of paraffin wax improves the efficiency of the solar water heating system, thus improving performance. In addition, Also presence of helical fins (TLF-PCM-HHF) model provides a better distribution and dispersion of the heat acquired from solar energy, transmitting it to the wax in both the charging and discharging states, thus registering an increase and improvement in the efficiency and performance of the solar heating system compared to the presence of wax alone (TLF-PCM) model.

Figure 13 and 14 show the temperature distribution contours for the TLF-PCM-HHF models,

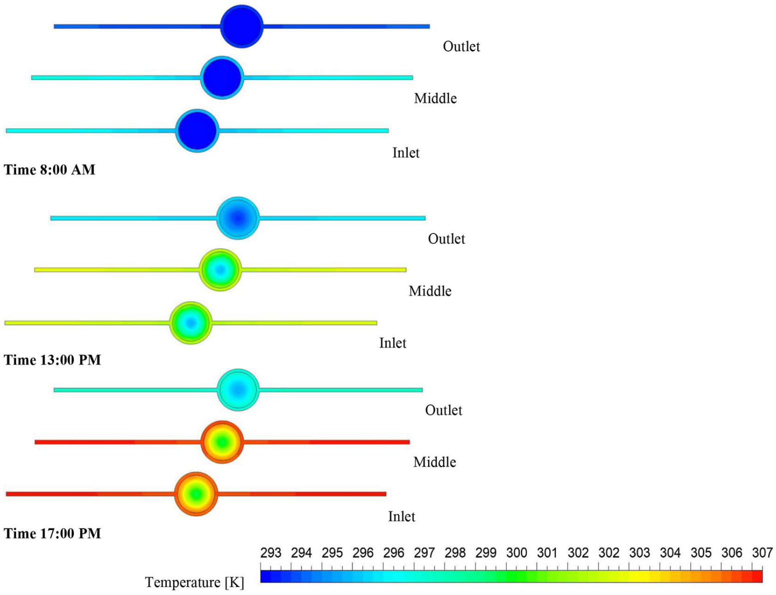


Figure 10. Temperature distribution contours in daylight hours for the (TLF) model

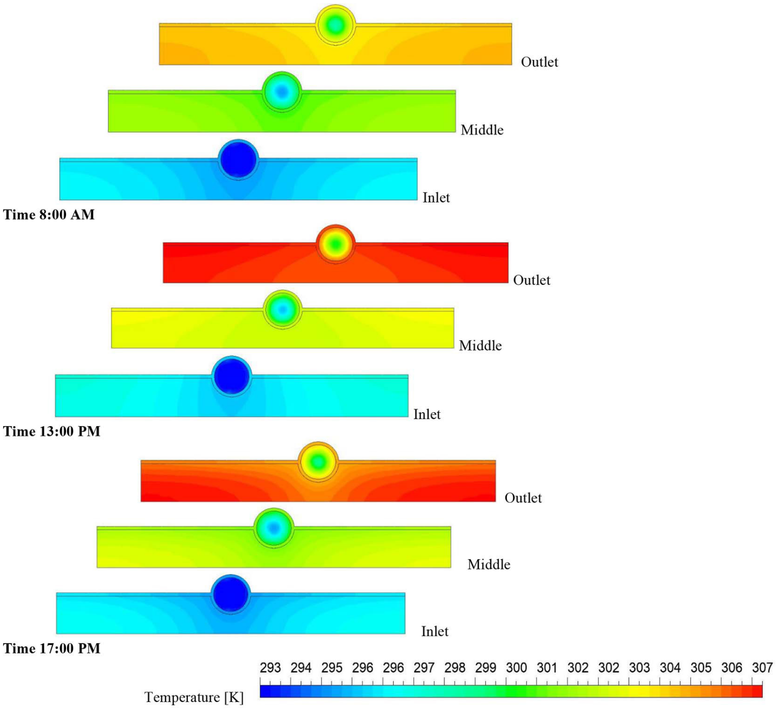


Figure 11. Temperature distribution contours in daylight hours for the (TLF-PCM) model

in the direction of water flow along the model, and at different levels and different times of the day. Figure 13 for level in center of the pipe, while Figure 14 in level mid of helical fins. It is clear from these contours that the temperature of PCM takes in same behavior of liquid fraction, increases with early hours of the day before noon, represented by the charging process of the PCM, and decreases with decreasing radiation after midday, represented by the heat dissipation process from the PCM to the water.

Previous studies have demonstrated that incorporating fins within phase change material systems significantly enhances heat transfer performance and accelerates the melting process. For instance, Ben Zohra et al. (2020) [25], they are reported improved thermal energy storage in PCM-integrated solar systems. The present

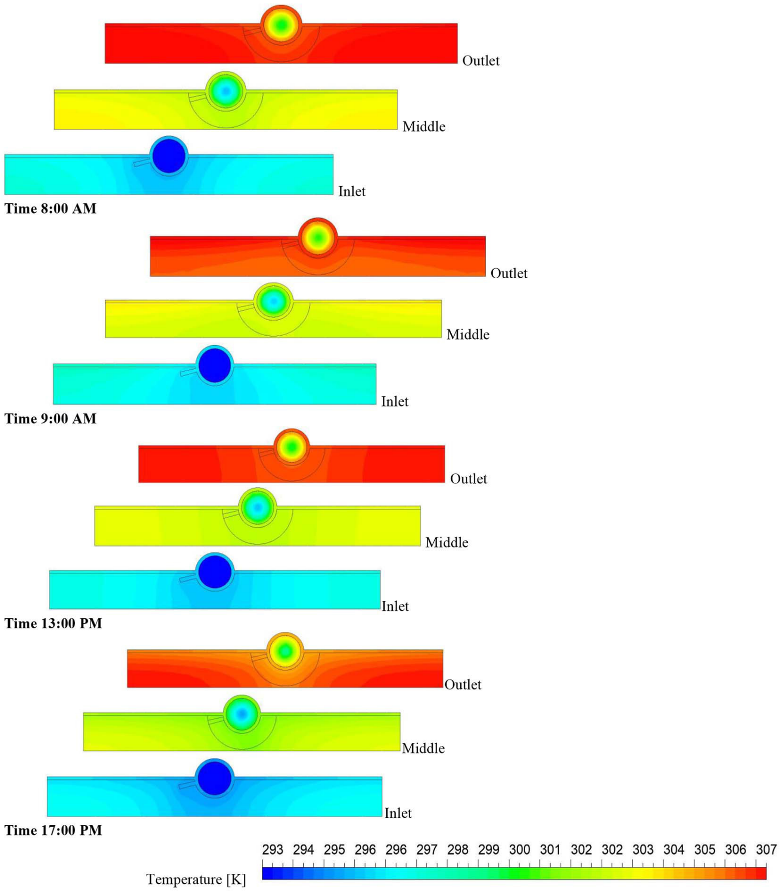


Figure 12. Temperature distribution contours in daylight hours for the (TLF-PCM-HHF) model

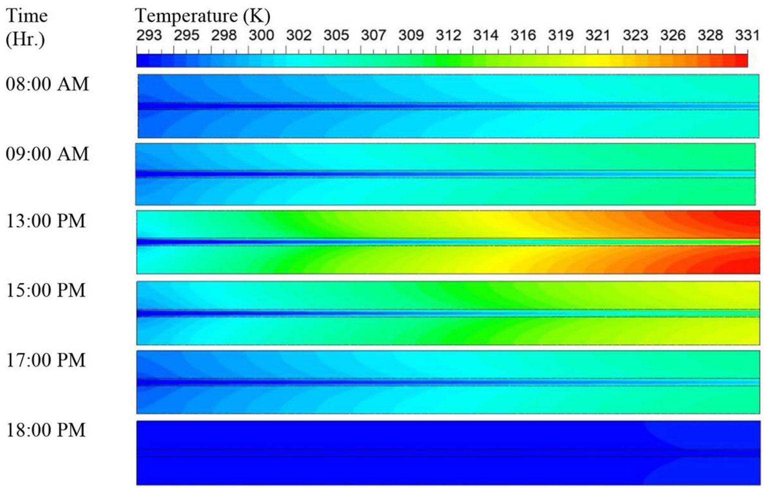


Figure 13. Temperature distribution contours in daylight hours for the TLF-PCM model

results are consistent with previously reported studies on phase change material-based thermal energy storage systems. For instance, the concluded results for the average of liquid fraction and temperature distribution for the proposed models in this study were compared with that got published results by Hasan and Suffer (2023) [15]. The predicted midnight water temperature was found to be 0.45% accurate in this comparissin. This ia indicating that the numerical model developed in this study can accurately simulate the thermal behavior of solar water heater systems integrated with PCMs. Moreover, Mahdi et al. (2019) [26] reported that heat transfer and melting time can

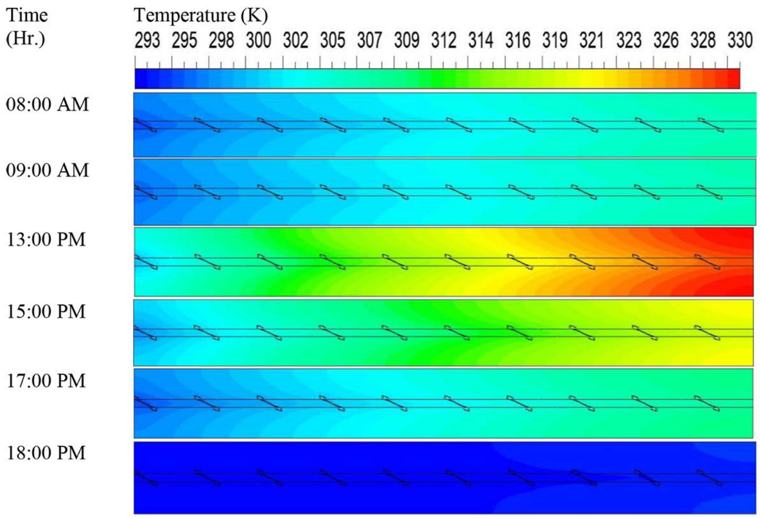


Figure 14. Temperature distribution contours in daylight hours for the TLF-PCM-HHF model

be improved in thermal systems based on helical fin configurations usingPCMs. These both comparisons demonstrate that the numerical simulation methodology based on enthalpy-porosity technique and finite volume discretization, provides reliable predictions of PCM melting and heat transfer performance.

CONCLUSIONS

Solar water heaters are among the most popular applications of solar energy. This study investigated improving the thermal performance of a solar water heater by conducting a numerical analysis of three proposed models. A single-tube design was proposed, given its complete symmetry with the other tubes and to minimize the load on the simulation software. The first model represents the conventional flat-plate solar water heater (TLF). The second model incorporates paraffin wax for thermal storage of the potential energy (TLF-PCM). Finally, the third model incorporates helical fins connected to the tube via a well-welded system, while retaining the paraffin wax (TLF-PCM-HHF). The design incorporates paraffin wax. The most important conclusions obtained from this numerical simulation were the possibility of storing solar energy in the storage material (paraffin wax) during daylight hours and utilizing this energy during the absence of sunlight or at night, while maintaining stable temperatures during the water heating process. Based on calculations of both Ra ≈ 2.3×10^3 and Ste ≈ 0.19, it was concluded that the true behavior of latent heat transfer during the melting of a PCM. The results also showed an increase in water temperature of 2 K during the period after midday, continuing until approximately 11:00 AM, compared to the conventional model where heating stopped at 5:00 PM, coinciding with sunset. As for the third model, which incorporates spiral fins, the results demonstrated improved heat transfer efficiency and a reduction in the time required for the paraffin wax to melt by 30–40% compared to the second model (TLF-PCM). Furthermore, the study achieved uniform heat distribution within the paraffin wax casing. Also from the results, it was concluded that the average melting rate (liquid fraction) of the TLF-PCM-HHF model was 9.33% better than that of the PCM-HHF model for the period from 2:00 p.m. to 8:00 p.m. The temperature distribution results at midnight were 300.37 K for the TLF model, and 302.043 K for the TLF-PCM model, and 304.360 K for (TLF-PCM-HHF) model. From the above conclusions its observed that this approach of adding phase change material for the purpose of thermal storage with the presence of helical fins reflects a good and real evaluation for improving the performance of the plate solar collector compared to what was achieved in previous studies, which allows for the acceptable evaluation of improving thermal performance.

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