Thermal Enhancement for Solar Water Heating System by Using Phase-change Materials

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Abstract: Thermal storage using phase-change materials PCMs is an efficient technique for enhancing the efficiency of solar energy utilization. This paper presents an investigation of solar thermal energy storage systems using an encapsulated PCM working in a realistic environment (Basra, Iraq). Numerical investigating the thermal performance of the heating system by using CFD technics with finite volume method .Water is used as the heat-transfer fluid HTF as well as sensible heat material. While paraffin wax packed in small cylindrical galvanized-iron capsules is used as the latent heat-PCM material. The capsules are integrated into a commercially cylindrical storage tank for hot water. First, the advantage of using flat plate solar collector FPSC and PCM is demonstrated on an insulated water tank. Finally, a turbulent-transient-3D model was developed using the ANSYS FLUENT 2020 R1 and compared with the experimental results. It was found in this case that the water temperature reaches above 50°C. Remained hot at least 25°C higher than the ambient temperature throughout 16 hours due to the presence of PCM. Parametric analyzes are performed to study the effect of the HTF flow rate (3 and 15lit/min) and the amount of PCM (5 and 10kg) on the PCM melting process, the charging time, and thermal storage energy of the water tank. The results indicate that the best performance can be obtained with the highest flow rate and the highest amount of PCM 15lit/min and 10kg, respectively, according to the current study. The results proved good agreement between the measured and numerical work.

Keywords: heat transfer-PCM-solar energy-FLUENT.

1 Introduction

Amongst many resources of alternative energy, solar energy is considered more promising because of its hygiene and availability in various places of the globe. The major component for any thermal storage application is the solar water heater collector (SWHC). With the use of a solar collector, the energy from solar radiation is converted to heat. Two types of storage systems are essentially built Sensible and latent heat storage. Both of them are combined to store a large amount of heat in a small unit volume thermal energy storage (TES) tank. Thermal energy storage in solar

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water heaters has recently emerged as an effective means of capturing and storing solar energy. In solar energy applications the time delay and usable power between the energy supply or production and its consumption, as well understood from engineering practice, is a significant problem. The PCM is the best option to get rid of this problem, due to its low cost, ease of use, and high storage capacity[1]. It is possible to classify PCMs into four various types as seen below **Figure 1 [2]**.
Several researchers had experimentally and numerically improved the thermal performance of the PCM in terms of operating time and storage energy capacity under an acceptable temperature range by incorporating it into storage tanks[1],[3],[4],[5], the benefit of this technique is to increase the thermal storage capacity, as researchers filled spherical or cylindrical capsules with PCM and integrated them into the storage tank. Or with solar collectors[6],[7],[8], this technology is beneficial because it prevents the loss of heat and energy in pipes or duct networks, and also in terms of cost as storage tanks and insulation material become unnecessary. The PCM was also integrated with the heat exchanger to release and absorb harvested energy in domestic applications[9],[10],[11]. Some researchers summarized techniques to improve the heat transfer of the PCM, either by using different types of PCM or by supporting it with materials that improve its efficiency. Cabeza et al.[12] experimentally studied the behavior of PCM (compound of a granular PCM graphite) in a TES at the University of Lleida, The researcher concluded that this module is very promising, even without exterior energy supply this technique will provide hot water for a long time. Beyne et al.[13] experimentally improved the heat transfer by treating the PCM material with metal foam (Aluminum and Copper) to raise its thermal conductivity, The results showed that adding metallic foam reduces cooling time by at least 25% compared to PCM without foaming. Kulkarni et al. [14] experimentally study the feasibility of storing solar energy using paraffin wax as PCM. The use helps to reduce the cooling rate of water; thus, it hence improves the efficiency of the system. Al-Kayiem & Lin [15] experimentally verified the system performance consisting of a flat plate solar collector integrated with a thermal energy storage tank for heating water in three cases with and without PCM (paraffin wax) and with Cu-PCM nanoparticles. The efficiency of the collector was improved with paraffin wax and Nano-composite by (6.9% and 8.4%), respectively. Sathiyaraj et al. [16] experimentally improved the PCM thermal conductivity for thermal storage (use paraffin wax as PCM) by boosting it with graphite powder. The results showed that the paraffin/graphite powder compound had better performance in heat transfer due to the high thermal conductivity (300 to 550 W/mK). Lu et al. [17] experimentally and numerically studied the performance of the Water Storage Tank containing two types of PCMs(CH3COONa·3H2O and C12H24O2) with various melting points, the increase in the amount of PCM had a significant influence on the heat release of the water tank. And others cited a mathematical model of PCM and different solution methods to model the phase-change using computational fluid dynamics of ANSYS FLUENT software. Bouhal et al. [18]numerically developed two heat transfer models for testing a TES containing PCM integrated with SWHC for domestic applications, the apparent heat capacity Cp^{app}technique and the enthalpy method, the results showed that the enthalpy method resulted in more computing time than the Cp^{app} model,

and the apparent heat capacity Cp^{app} technique is suitable during the phase change process. Abdulrahman et al.[10]numerically verified the effect of the PCM melting process.

The present work aims to perform experimental and numerical verification to analyze the performance of thermal storage for the storage tank integrated with paraffin wax as a PCM is packed in cylindrical capsules used in the domestic hot water DHW system under environmental conditions (Iraq, Basra). Numerical simulations of the 3D turbulent flow transient model are performed by solving the governing equations. The experimental and numerical procedure is done by controlling the mass of PCM and the flow rate of HTF. Then comparing the results for verification.

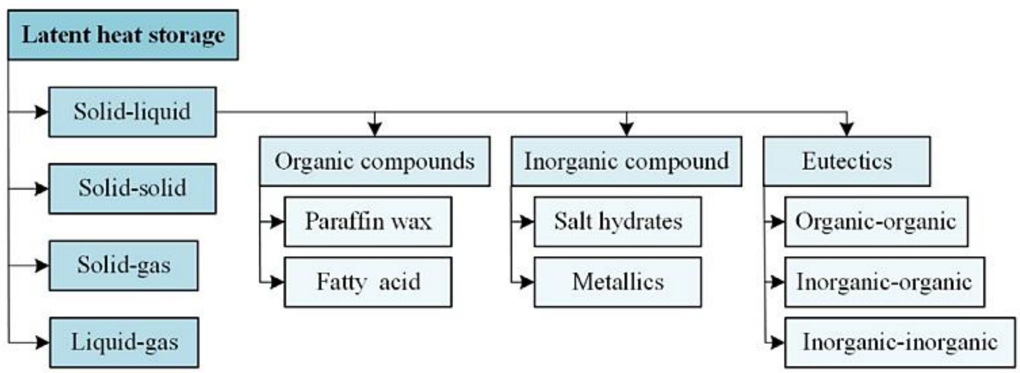

Fig. 1. Categories of LHS and classification of PCMs **[2].**

2 Experimental Discretion

2.1 Experimental setup

The photographic image and schematic diagram are seen in **Figures (2and 3)**, respectively, of the experimental setup. The setup is consisting of a flat plate collector (1*1) m^2 by a tilt angle of 30°. Which has a glass cover, absorber plate of galvanized steel with 0.01cm thick, 17 m of copper pipe, and an insulation frame with a thickness of 3 cm. Connected to the main supply of water and the storage tank (40cm diameter/120cm height with 138liters capacity). Integrated with cylindrical capsules (2cm diameter/25cm height). Paraffin wax is utilized as the PCM in this study, where 40 samples are used by a total of 10 kg of paraffin, 0.25kg of paraffin is packed in each cylindrical capsule and the material of the cylindrical capsules is galvanized iron. 22K-type thermocouples with an accuracy of (±0.1∘C) are placed at the inlet, outlet, and each three are distributed at the lower, middle, and upper sections of the tank. Five are inserted in a PCM capsule at equal interval space at the central section of the tank. Also, one to measure the temperature of ambient air. The accuracy of the flow-meter is (±0.2lit/min) to measure the heat transfer fluid rate.

2.2 Experimental procedure

The performance of TES to thermal storage is studied using (3lit/min and 15lit/min) flow rates. With varying inlet HTF temperatures and water volume 60liter with and without the PCM into the tank. Also, by controlling the amount of PCM. The readings are recorded during the day for 16hour which started at 9:00 am. Every 30minutes the PCM and HTF temperature are measured. The stored thermal energy within the capsules is kept until the PCM approaches its melting point. Finally, the PCM heats up to the point of being superheated, the energy is then deposited in liquid PCM as sensible heat. The experiments were conducted during November-2020 under the environmental conditions of Karma-Ali district at (Iraq/Basra), this site is located at 47.8°E and 30.5°N.

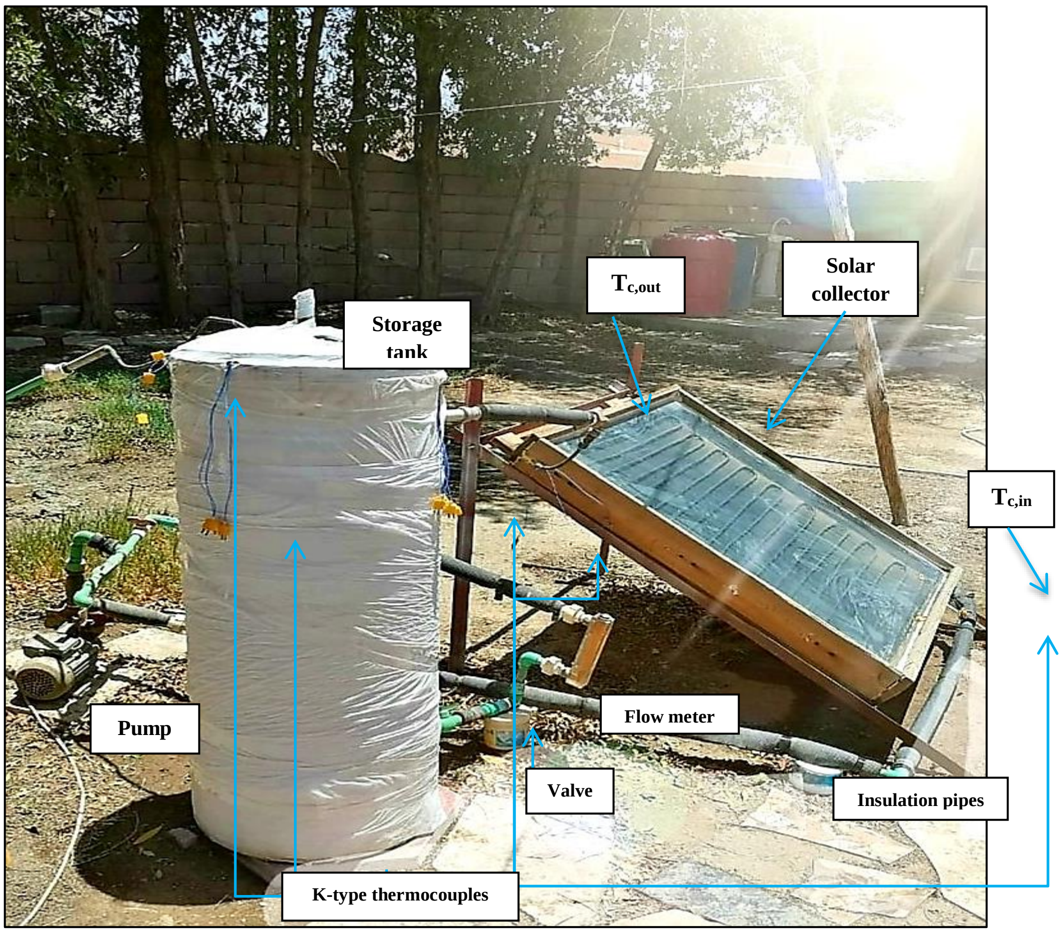

Fig. 2. Photograph view of the experimental setup.

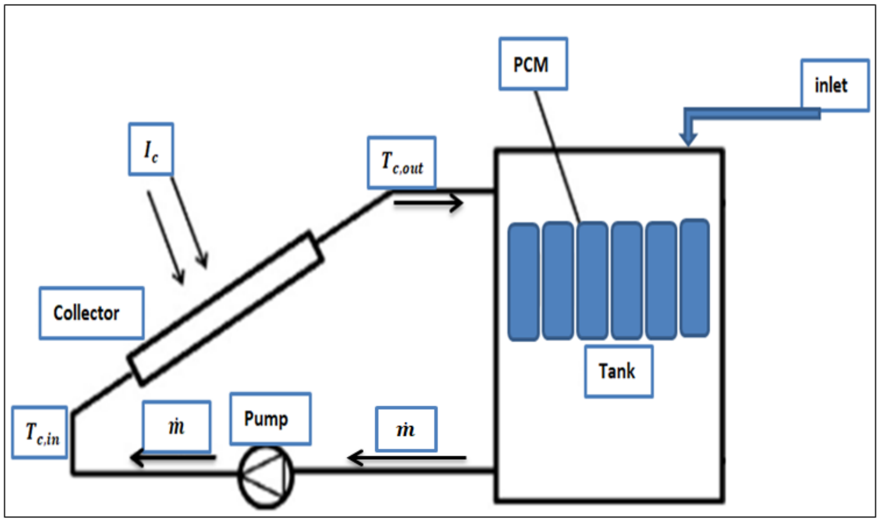

Fig. 3. Schematic diagram of the experimental test rig.

3 Theoretical Analysis

3.1 Mathematical Model

3.1.1 Physical descriptions

Figure 4. depicts a schematic 3D-computational model for the stored thermal energy. It consists of a TES tank integrated with PCM's cylindrical capsules with a dimension of 40cm diameter/48cm height of TES tank filled by water, and 2cm diameter/25cm height of capsules which are packed with paraffin wax as PCM material after melting to form the heat-absorbing part of the hot water. The cylindrical capsules of the PCM are arranged one level and spaced instead of one unit, to increase the surface area of the convection. Due to the transmission of heat from the HTF to the PCM, the PCM melts and turns from the solid phase to the liquid. Numerical simulation is performed by controlling the mass of paraffin wax (5kg and 10kg) and the water flow rate (0.05kg/s and 0.25kg/s).

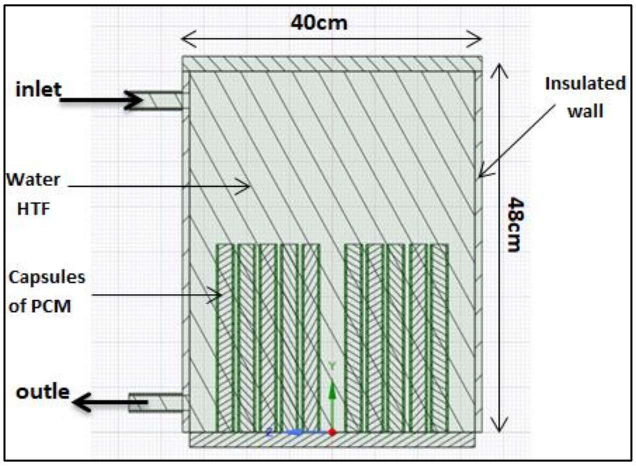

Fig. 4. Schematic of section mode 3D-computational model.

3.1.2 Assumption:

A transient flow model during the PCM melting process of the TES tank is developed using the following:

- PCM melting process is transient and 3D model with temperature variations is used.
- Flow is Turbulent.
- The fluid is Newtonian and Incompressible.
- The PCM is isotropic and homogeneous.
- For PCM and water, thermo-physical properties are constant.
- For PCM a negligible volumetric expansion.
- Heat transfer by radiation is neglected. Energy fluxes are exchanged between PCM and fluid, and loss through the wall of the tank.

PCM

$$m^{pcm}c^{pcm}\frac{dT^{pcm}}{dt} = \dot{Q}^{pcm}_{cond} + \dot{Q}_{\mathrm{w}} \tag{1}$$

Fluid

$$m^{w}c^{w}\frac{dT^{w}}{dt} = \dot{Q}^{flow} + \dot{Q}^{pcm/w}_{conv} + \dot{Q}_{loss} \tag{2}$$

where $\dot{Q}^{flow}$ is the energy change by the direct inlet-outlet flow counting the flow in both directions. upward/downward. $\dot{Q}_{loss}$ is the convection heat loss from the top and bottom of the cylindrical tank bases to the environment.

3.1.3 Governing equations:

The governing equations are applied based on Navier-Stokes and energy equations for the thermal storage tank these can be expressed as follows:

The continuity equation:

$$\nabla \cdot u = 0$$

(3)

The momentum equation:

$$\rho_f \frac{\partial u}{\partial t} + (\rho_f \cdot u \cdot \nabla)u = -\nabla p + \nabla \cdot (\mu_f \cdot \nabla u)$$

(4)

The energy equation:

$$\rho_f \cdot C_f \cdot \frac{\partial T}{\partial t} + \rho_f \cdot C_f \cdot u \cdot \nabla T = \nabla \cdot (\lambda_f \cdot \nabla T)$$

(5)

The PCM phase transformation are solved by using the Enthalpy formulation method, this method assumes that enthalpy H is an amount of ‘h’ and latent heat ‘ΔH’

$$\rho_p \cdot \frac{\partial H}{\partial \tau} = \lambda_p \cdot \nabla^2 \cdot T$$

(6)

$$H = h + \Delta H$$

(7)

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT$$

(8)

where h_{ref} and T_{ref} are represented by the reference enthalpy and the reference temperature, respectively.

$\Delta H = \beta \cdot L$

(9) $\beta = \begin{cases} 0 & T < T_S \\ \frac{T-T_S}{T_L-T_S} & T_S < T < T_L \\ 1 & T > T_L \end{cases}$

(10)

3.1.4 Initial and boundary conditions

In this study, two cases were investigated with amounts of PCM (5kg and 10kg) and water as a working fluid. The mass-flow was set as the boundary conditions of inlet and outlet. The initial temperature of the TES tank was 291 K, the inlet water temperatures were (313k and 323k), and the inlet mass-flow rates were (0.05 kg/s and 0.25 kg/s).

$t = 0,\ T_{(x,y,z,t=0)} = 291k$

(11)

On the wall, there was a no-slip condition. for example, the water velocity was zero near the wall:

u=v=w= 0

(12)

Keeping the wall, top, and bottom wall boundary conditions adiabatic.

$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$

(13)

The limits for the inlet water are:

$t > 0, T = T_{in}\ , \dot{m} = \dot{m}_{in}$

(14)

3.2 Numerical analysis

Using ANSYS workbench 2020 R1 the geometry and mesh are constructed for the model and the Computational methodology is performed to solve the governing equations (3), (4), and (5) for transient turbulent flow using CFD (FLUENT) software. To simulate the heat transfer and hydrodynamic problems. Numerically, by using the finite volume method FVM the governing equations are solved. In the first step, the computational model is divided into elements. The mesh model is created by using tetrahedral cells and consists of 112633 elements. From solution methods SIMPLE (Semi-Implicit-Method for Pressure- Linked-Equations) algorithm is used for the pressure-velocity coupling and Second-order upwind is selected. Also, the turbulence models *k-epsilon* description and is solved in a pressure-based solver. The solution process based on convergence criteria 10^{-6} and for energy is within 10^{-3}. The residuals definition is shown as follow[19]:

$$R = \frac{\sum_{cellp} \left|\sum_{nb} a_{nb}\phi_{nb} + b - a_p\phi_p\right|}{\sum_{cellp} \left|a_p\phi_p\right|}$$

The utilized time step is set to 10s in calculations and the maximum number of iterations per time step is set as 20.

4 Result and Discussion

- **Energy calculation for the thermal water tank**

For investigating the influence of the PCM on the thermal energy storage $Q_{storage}$ in this study. The thermal energy when without and with PCM in the water tank is calculated according to follows, respectively:

Sensible heat stored $\longrightarrow$ $Q_{storage} = m \cdot C_p \cdot (T_{\text{hot}} - T_{\text{cold}})$
(15)

Latent heat stored $\longrightarrow$ $Q_{storage} = m \cdot c_{p,s} \cdot (T_m - T_i) + m \cdot \beta \cdot \Delta h_m + m \cdot c_{p,l} \cdot \left(T_f - T_i\right)$
(16)

The second term in equation (16) is solved depending on the relationship (10) mentioned above. This section includes analysis of experimental and computational results depending on the various variables based on their importance with 60lit of water.

i. Effect of the HTF Inlet temperatures by using FPSC

Figure 5. shows the time variation temperatures of the PCM, water at the tank, and the temperature of ambient air, on November 9 with flow-rate 15lit/min and 5kg of PCM. It can be noted that at the beginning of the operation, the water temperature rises at a quicker rate associated to the temperature of the PCM which is initially in the solid phase. Until it reaches a temperature of about 50°C, which is approximately equal to the aforementioned melting temp. From there, the PCM gradually turns into the liquid phase as a result of absorbing heat from the water. After turning off the system and closing the valves, the water temperature decreases by 2-3°C below the PCM temperature and continues to decrease. At this stage the PCM keeps releasing the heat into the water, thus reducing the rate of water temperature drop. From another aspect, we note the big difference in the ambient air temperature for water and PCM.

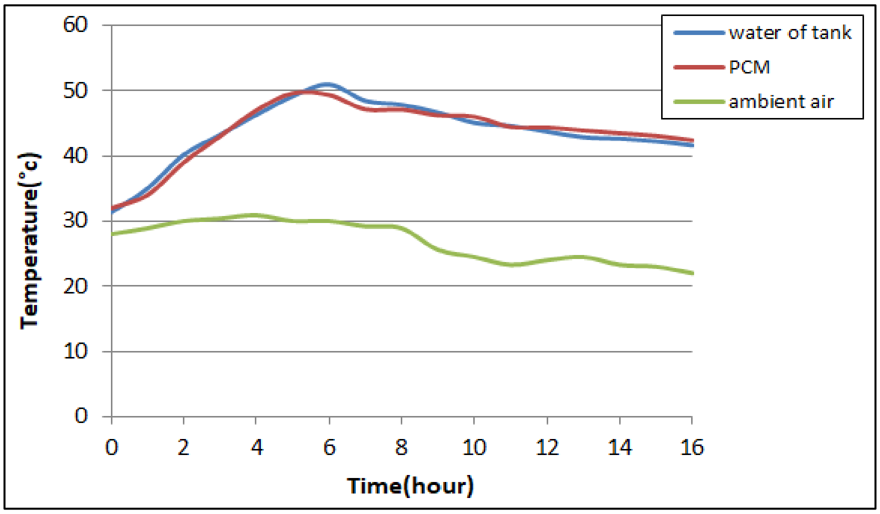

Fig. 5. Time variation temperatures of the PCM, the water of the tank, and the ambient air.

ii. Effect of the flow rates of HTF

Figure 6 illustrates the influence of changing HTF flow rates (15lit/min and 3lit/min) at (November 9 and 20), respectively, during system operation with 5kg of PCM into the tank and variable inlet temperatures of HTF. The effect of varying the flow rate can be observed on the melting process, the charging time, and thermal storage energy. As the graphs show that the time required for the PCM and the water to reach the maximum temperature is about 50-52°C less with a flow rate of 15lit/min compared to 3lit/min. Throughout the operation period, the rate of heat transfer from the HTF into the TES tank to the PCM and the water is slightly higher for the flow rate of 15lit/min. Concerning the PCM, the increase in the flow rate has a significant effect on the phase change of the PCM from the solid phase to the liquid, as the arrival time of the PCM to the melting point as shown in the graph is approximately 52°C with a flow rate of 15lit/min less compared to 3lit/min. This is attributed to an increase in the surface heat transfer coefficient of PCM-water. The flow rate effect is also evident in the thermal storage capacity. With an increase of 15lit/min the storage capacity increases to over 1000KJ compared to 3lit/min. All This means that the heat absorbed from the FPSC and transported by the HTF to the tank is affected by the HTF flow rate.

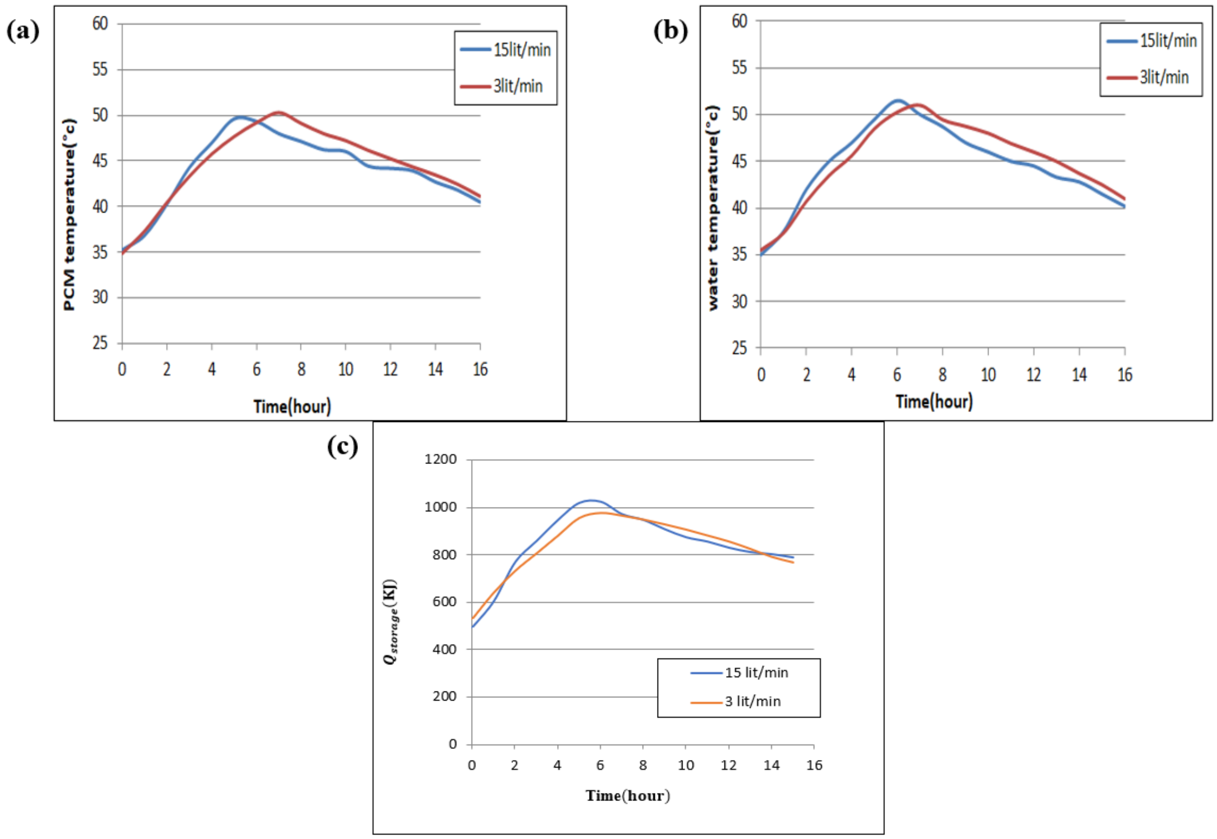

Fig. 6. Effect of HTF flow rate on (a) PCM melting process, (b) charging-time, and (c) thermal energy $Q_{storage}$ of the water tank.

iii. Effect of varying the PCM mass

The effect of using different PCM towards thermal storage is studied. 5kg and 10kg of paraffin wax were added to the storage tank with 60liters of water. The temporal variance of water temperatures is compared with (5and10kg) PCM and without it at (November 9, 20, and 23), respectively. As shown in **Figure 7**, although the maximum water temperature exceeds 50°C and is nearly close in all three cases. The water gains and loses heat at a faster rate without PCM during the first 6h of operating the system compared to the other cases. Whereas, water with 10kg PCM gains and loses heat at a slower rate compared to the other cases. This is due to the solid PCM absorbing heat from the water and turning it into the liquid phase during the charging period and releasing it during gradual solidification for PCM to water about 10h after switching off the system.

The storage tank with 10kg PCM is maintaining the water temperature better than the other two cases by 6-5°C.

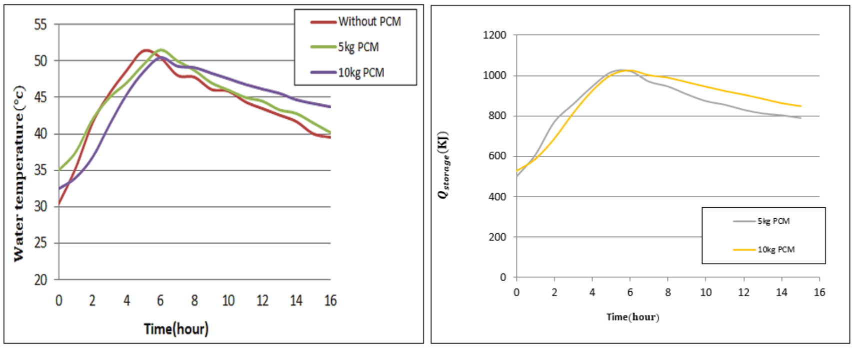

Fig. 7. Comparison of the water temperature difference and thermal energy $Q_{storage}$ for a variant amounts of the PCM.

iv. Comparison between the Experimental and Numerical Analysis

The same procedures were applied and used for both the experimental and numerical models. The volume of water inside the tank was 60liters with 5kg of PCM approximately 20capsules (2cm diameter/25cm height). The initial temperature of the TES tank was 291K, the inlet water temperatures were (313k and 323k), and the inlet mass-flow rates were (0.05kg/s and 0.25kg/s). The effect of changing the mass rate of HTF based on thermal energy was studied. **Figure 8(a)** and **(b)** compares the experimentally and numerically calculated thermal energy of the water tank according to equation (16), as a function of time for the different flow rates (0.05kg/s and 0.25kg/s). Where the outcomes indicate that the experimental results are identical to the results of the numerical simulation.

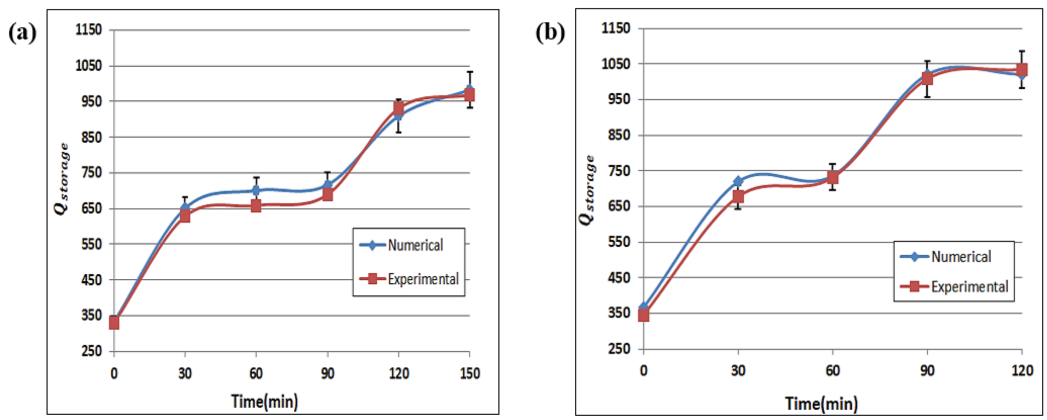

Fig. 8. Thermal storage energy $Q_{storage}$(**KJ**) of the TES tank as a function of time for the different flow rates, (**a**) at a flow rate ($\dot{m}$= 0.05 kg\s), **(b)** at flow rate ($\dot{m}$= 0.05 kg\s).

5 Conclusions

In this study, an experimental and numerical model was used to verify the thermal energy storage integrated with a PCM material of paraffin wax to using hot water for the DHW system to at an average temperature more than the nominal temperature. ANSYS FLUENT 2020 R1 is adopted to solve the governing equations of the transient-3D mathematical model. The following is concluded based on experimental and theoretical results:

1. Experimental results have proven the best performance of the TES system by using the solar collectors and PCM that to get hot water for a long time after the switch-off the system or the termination of the input heat energy. The water temperature was kept above 42°C in all climatic and operational conditions.
2. Flow rates of HTF have a significant effect on PCM melting process and charging time. Which were reduced by 2hour at the flow rate is increased from 3 to 15lit/min.
3. Thermal storage energy of water tank with PCM increases to over 1000KJ at 15lit/min.
4. It is observed, that the addition of PCM into a storage tank increases the energy stored and this raises with the amount of PCM. Based on the above results, 10kg paraffin wax achieves superlative PCM mass to be integrated with storage tank due to its potential to store large energy and maintain the water temperature better than cases of 5kg and without PCM by 6-5°C.References

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