

Experimental and Numerical Investigation of the Thermal Performance of Paraffin-Based PCM Encapsulated in Different Metallic Capsules for Solar Water Heating Systems

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Abstract - However, the thermal performance of latent heat thermal energy storage systems using PCM is significantly affected by the thermal properties of the capsule materials used. In spite of the above, not much research effort has been devoted to the impact of the encapsulation material thermal properties in solar water heaters applications. The present study focuses on the investigation of the effect of metal encapsulation materials on the performance of latent heat thermal energy storage system based on paraffin PCM coupled with a forced circulation solar water heater system. An experimental facility equipped with SCADA-based data acquisition system and a 3D transient CFD model were built using ANSYS Fluent for aluminum, cast iron, and stainless steel capsules.

It can be seen from the results obtained that the thermal conductivity of the encapsulation material is the key determinant of the charging operation. In particular, the highest performances in terms of maximum collector thermal efficiency (64.3%), maximum stored thermal energy (4320 kJ), and maximum latent heat storage (2200 kJ) were reached by aluminium compared to cast iron and stainless steel. The numerical model proved to be a valid tool in describing the transient thermal behavior of the system with RMSE of 0.82 °C, MAPE of 1.56%, and R² of 0.991. Moreover, temperature contour analysis revealed that higher uniformity of the temperature distribution and faster PCM melting could be achieved by choosing aluminium due to its high thermal conductivity.

Thus, the proposed approach of experimental and numerical analysis proves to be an effective tool in assessing different encapsulation materials and optimizing PCM solar thermal energy storage systems. The obtained results show that high-conductivity encapsulation materials considerably improve the charging performance.

Key Words: Solar hot water heating system, Phase change material, Numerical modeling, Capsule material, Latent heat storage

1.INTRODUCTION

With regard to the increasing global need for energy, the depletion of fossil fuels, and environmental threats related to carbon dioxide, there is an increased shift towards sustainable sources of energy worldwide. With all the possible sources of

renewable energy, solar energy is considered to be one of the most abundant, environment friendly, and geographically available forms of energy. It has attracted substantial research attention due to its ability to lessen our dependency on conventional fuels and improve energy security. One of the most successful uses of solar thermal energy is solar water heaters (SWHs). SWHs are those systems which directly use the energy of the sun for heating purposes to increase the temperature of water through the conversion of sunlight into heat. The usage of SWHs can significantly lower the amount of electrical energy needed to heat water and decrease the emission of CO₂. However, although such systems have several benefits, their thermal performance depends on the intermittency of solar radiation and, therefore, changes in weather conditions and seasonality affect the temperature and amount of hot water [1].

In order to address these challenges, thermal energy storage (TES) is now an essential part of current solar thermal systems. With TES, excess energy is stored during times of high solar irradiation and used in the absence of solar energy. Thus, TES improves the system stability, operational hours, and energy use from renewable sources. According to the type of storage, TES systems can be divided into sensible heat storage, latent heat storage, and thermochemical energy storage systems. Among these methods, LHTES that uses phase change materials (PCMs) for energy storage has gained much interest due to high energy storage density, almost isothermal phase change, small size of the storage system, and high potential to improve the thermal efficiency of solar energy systems [2,3].

Paraffin wax is one of the popular PCM materials being employed in solar thermal systems due to its favorable melting point for hot water generation at home, latent heat of fusion, chemical stability, absence of supercooling effect, low vapor pressure, non-corrosiveness, and durability. However, poor thermal conductivity of paraffin is one of the major drawbacks that greatly affect the performance of latent heat thermal energy storage systems through slowing down the heat transfer process during the charging and discharging phases. This drawback remains one of the major obstacles hindering the adoption of solar water heaters based on PCM technology [2,3].

For the purpose of addressing this issue, various methods for enhancing heat transfer have been suggested in the last two decades. Such methods include the use of metallic fins, porous materials, metal foams, nanoparticles, heat pipes, geometric

optimization of heat exchangers, hybrid thermal storage designs, and encapsulation. Of these various methods, the method of encapsulation is considered as one of the most practical industrial choices as it not only avoids the risk of the leakage of PCM during its melting process but also provides protection to the storage material from environmental hazards, increased heat transfer area, and ease of incorporation into the thermal storage tank. However, besides the thermophysical properties of the PCM, the efficiency of the encapsulation process is also influenced by the thermophysical and physical properties of the chosen encapsulating material such as thermal conductivity, mechanical strength, corrosion resistance, wall thickness, manufacturability, durability, and economics.

In the last several years, considerable improvements have been made in the design of thermal energy storage technologies using PCM technology for solar thermal applications. There is a number of review articles that give an overview of the recent progress in integrating PCM technology with solar collectors, solar water heaters, and latent heat thermal energy storage devices, outlining the important technical problems that hinder the wide adoption of solar thermal technology. As mentioned in Mourad et al., [4], improving the heat transfer in PCM thermal energy storage systems is considered one of the most important problems that influence the practical application of solar thermal systems. At the same time, in their review article, Chekifi et al., [5] point out the importance of micro- and nano-encapsulation technology in order to improve the thermal stability of the device, to prevent material leaking, and to increase its reliability during its operation. The recent review paper by Hamzat et al., [6] concludes that further development should concentrate on sustainable encapsulating materials, environmentally friendly PCMs, and new methods of increasing heat transfer. These statements are confirmed by the recent comprehensive reviews on latent heat thermal energy storage systems presented in the Journal of Energy Storage.

Further building up from the literature reviews, many experiments have been carried out on improving the thermal performance of solar water heating systems assisted with PCM through different modifications in encapsulation materials, storage arrangement, and collectors. The earliest work that has dealt explicitly with the issue of choice of encapsulation materials is done by Reddy et al. [19] in which they have performed an experimental analysis on paraffin wax encapsulated in aluminum, mild steel, and HDPE spheres. Although the experimental findings reveal some insignificant variations in charging and discharging time between the three materials under consideration, the experimental set-up is quite simple and lacks any proper instrumentation for assessing the impact of materials on heat transfer efficiency.

Further research has focused on other parameters related to the design of solar water heating system. According to Asif et al. [20], aluminium-built in storage solar water heater is more thermally efficient than stainless-steel built in storage solar water heaters due to high thermal conductivity of aluminium. Nonetheless, their study has not considered the use of latent heat thermal energy storage or PCM encapsulation, thus making their results less relevant for the modern PCMs systems. On the contrary, Nadjib et al. [21] have analyzed the impact of the position of capsules in terms of thermal stratification and hot water supply duration and found out that optimal placement of PCM capsules increases the system performance. Similarly, Patel and Rathod [22] have analyzed the influence of capsule shape by using spherical and rectangular PCM capsules, finding that optimal shapes

improve the heat storage properties of the system. Still, both of these studies have used the same encapsulation material.

Meanwhile, great progress has also been made in heat transfer improvement of photovoltaic-thermal (PV/T) systems. In their experimental, theoretical, and review works, Ahmed et al. [9–13] established the use of porous materials, glass covers, and hybrid water-air heating designs as a way of increasing thermal energy storage, efficiencies of collectors, and overall system stability. They emphasized that thermal energy storage improvement and heat transfer enhancement would be among the key areas to focus on for future solar thermal energy systems. Likewise, in their works, Aljumaily et al. [14–17] explored various ways of improving latent heat thermal energy storage such as optimal heat exchanger designs, rotating shell-and-tube design, and hybrid PCM-based photovoltaic cooling systems. They concluded that the improvement of heat transfer mechanisms via conduction and convection greatly enhanced the charging and discharging rates of PCMs. Moreover, in their numerical studies of geothermal assisted energy systems, Abeda et al. [18] once again confirmed the importance of efficient thermal management and heat transfer.

As a whole, all these research studies indicate substantial advancements in PCM formulations, encapsulation techniques, heat exchanger designs, and thermal management. However, most of the earlier studies concentrated on either PCM composition, collector design, storage arrangement, or capsule shape while the effect of metallic capsule material has not been studied adequately. Thus, there is no information about the separate role of the capsule material on the charging performance of the latent heat thermal energy storage system.

Although substantial progress has been made in PCM assisted solar thermal energy storage systems, most of the investigations have been concentrated on the choice of PCM, geometry of heat exchanger, capsule layout and heat transfer augmentation strategies. On the other hand, little work has been done on the effect of metallic enclosure materials on transient behavior of PCM under similar operational conditions. In addition, not many investigations have been conducted that have used a combination of both comprehensive experimental data and verified 3D-CFD simulation models to quantify their performance as well as provide insights into the physics of the heat transfer phenomenon.

In this context, current investigation presents an experimental and numerical analysis of the effect of aluminum, cast iron and stainless steel enclosure materials on the charging behavior of latent heat thermal energy storage based on paraffin in forced circulation solar water heating system. An experimental facility complete with SCADA-based measurement system was designed, whereas a 3D transient ANSYS-Fluent model was constructed and verified against experimental results.

What makes this study unique is that the standard experimental technique is applied along with the validated 3D CFD model to investigate the performance of metallic material for encapsulation under the same working conditions. What makes this study different from previous studies is that the thermal performance assessment, validation of numerical simulation, calculation of temperature distribution field, and engineering evaluation are conducted.

2. MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP

An experimental set up was specially designed to study the thermal performance of a paraffin based latent heat thermal energy storage (LHTES) unit integrated with a forced circulation solar water heater. The system consisted of flat plate solar collector, insulated storage tank with encapsulated PCM modules, closed-loop hydraulic circulation circuit with a circulation pump, valves and flow-control devices and SCADA based monitoring system for continuous thermal and hydraulic data acquisition. The commercial paraffin wax was chosen as the phase change material due to its favourable thermophysical properties for low temperature thermal energy storage [10]. The PCM was encapsulated in cylindrical capsules of aluminium, cast iron and stainless steel with the same dimensions (200 mm length, 50 mm outer diameter and 2 mm wall thickness) and the same mass of PCM, so that the encapsulation material was the only variable under investigation. The thermal energy that was gained from the collector was transferred from the circulating water to the storage tank, where it was stored as sensible heat of the water and latent heat of the PCM that is present in the encapsulation. In order to provide a valid comparison, all operating conditions such as the orientation of the collector, geometry of the storage tank, amount of water, mass of the PCM, size of the capsule, flow rate, and placement of the sensors were kept unchanged in all the tests.

2.2 INSTRUMENTATION DATA ACQUISITION

The experimental installation was equipped with a SCADA based data acquisition system that allowed ongoing monitoring and automatic recording of all operational parameters. A calibrated set of thermocouples was mounted on the inlet and outlet of the collector, storage tank, PCM capsules and in the ambient environment. Water flow rate and solar irradiance were measured by a flow meter and a pyranometer respectively. All measuring devices were interconnected in the single SCADA system, which enabled simultaneous acquisition, visualization and storage of experimental data. This process ensured that no human error could be made and ensured the accuracy of the data collection of the experiments. Technical specifications of measurement equipment are shown in Figure 4 and Table 3.

2.3 THERMOPHYSICAL PROPERTIES OF THE PHASE CHANGE MATERIAL

The phase change material selected was commercial paraffin wax, due to its appropriate melting point, high latent heat of fusion, thermal stability, negligible supercooling and chemical stability under low temperature conditions. Table 4 Properties used in the experimental study and the numerical models All property values were assumed to be constant over the temperature range studied unless otherwise stated.

2.4 EXPERIMENTAL PROCEDURE

All experiments were conducted according to a standard procedure to ensure consistent measurements and reliable comparison between the various encapsulation materials tested. Before each experiment, the solar water heating unit and all the instruments used were checked and calibrated according to the manufacturer's specifications. The PCM was allowed to solidify before the storage tank was filled with the given amount of water and the capsules were placed in the same positions. All the experiments were carried out under similar outdoor conditions from 08:00 to 19:00 h. While

charging the heat exchanger, the values of solar radiation intensity, ambient temperature, collector inlet and outlet temperatures, storage tank temperature, PCM temperature, and flow rate of water were monitored and recorded. The acquired data were subsequently processed to evaluate the thermal performance of the investigated PCM encapsulation materials.

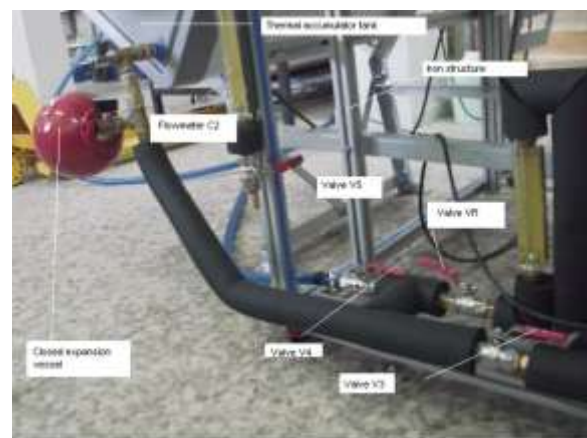


Fig-1. Overall view of the EDIBON EESTC experimental platform.

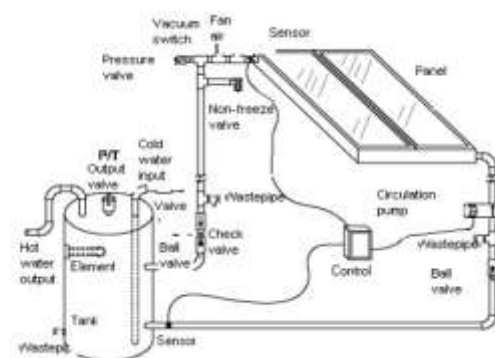


Fig-2. Schematic diagram of the EESTC solar thermal energy system.



Fig-3 : Cylindrical PCM capsules fabricated from aluminum, cast iron, and stainless steel

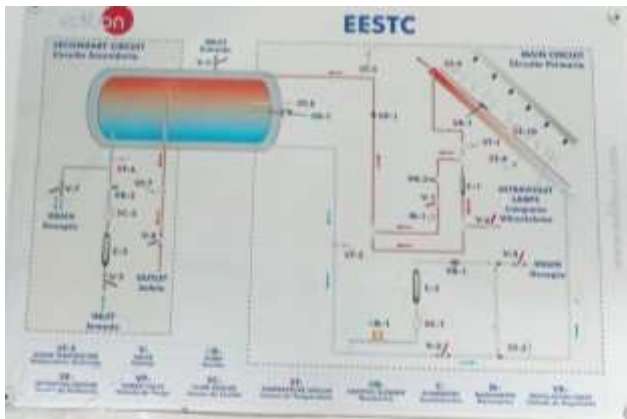


Fig-4. Instrumentation panel showing sensor connections.

Table-1. Main Components of the Experimental Platform

Component	Function
Flat-plate solar collector	Converts incident solar radiation into thermal energy
Insulated storage tank	Stores sensible and latent thermal energy
Encapsulated PCM modules	Store latent heat during phase transition
Hydraulic circulation loop	Transfers thermal energy between collector and storage tank
Temperature sensors	Measure temperatures at multiple locations
Solar radiation sensor	Measures incident solar irradiance
Flow measurement device	Measures water flow rate
SCADA system	Real-time monitoring, visualization, and automatic data acquisition

Table-2: Thermophysical properties of the metallic encapsulation materials used in the numerical simulations.

Property	Aluminium	Cast Iron	Stainless Steel	Unit
Density	2700	7200	7850	kg m ⁻³
Thermal conductivity	237	55	16.2	W m ⁻¹ K ⁻¹
Specific heat	897	460	500	J kg ⁻¹ K ⁻¹

Table-3 Instrumentation and Measurement System of the Experimental Platform

Parameter	Instrument	Symbol	Unit	Purpose
Solar irradiance	Pyranometer	SR-1	W/m ²	Solar energy input
Ambient temperature	Temperature sensor	ST-1–ST10	°C	Environmental condition
Collector inlet temperature	Thermocouple	ST	°C	Collector performance
Collector outlet temperature	Thermocouple	ST	°C	Useful heat gain
Storage tank temperature	Thermocouple	ST	°C	Storage evaluation
PCM temperature	Thermocouple	ST	°C	Charging/discharging analysis
Water flow rate	Flow meter	SC-1, SC-2	L/min	Heat transfer calculation
Data acquisition	SCADA	—	—	Continuous monitoring

Table-4: Thermo-physical properties of PCM [14-17].

Material properties	PCM
Melting Temperature [K]	334
Density in solid state [kg/m ³]	894.56
Density in liquid state [kg/m ³]	783.42
Specific heat in solid state [J/kg K]	1659
Specific heat in liquid state [J/kg K]	2460
Latent heat of fusion [J/kg]	235512.5
Thermal conductivity in solid state [W/m K]	0.259
Thermal conductivity in liquid state [W/m K]	0.158
Dynamic temperature [kg/m s]	0.01405
Solidus Temperature [K]	318.5
Liquidous temperature [K]	339
Thermal expansion coefficient [1/K]	0.000307

2.5 THERMAL PERFORMANCE EVALUATION

The experimental data obtained from the SCADA system were analyzed to assess the thermal performance of the latent heat thermal energy storage (LHTES) system. The recorded parameters included solar irradiance, ambient temperature, collector inlet and outlet temperatures, storage tank temperatures, PCM temperatures, and water flow rate. These experimental data were subsequently used to calculate the useful heat gain, thermal energy stored, collector thermal efficiency, and charging characteristics of the PCM.

The useful thermal energy transferred to the working fluid was calculated using the first law of thermodynamics as follows:

$$Q_u = \dot{m} \cdot C_p (T_o - T_i) \dots\dots\dots(1)$$

where Q_u (W) is the useful heat gain, $\dot{m}$ (kg S^{-1}) is the mass flow rate of water, C_p (J $Kg^{-1} K^{-1}$) is the specific heat capacity of water, and T_o and T_i (°C) represent the outlet and inlet temperatures of the solar collector, respectively.

The total thermal energy stored in the storage tank is the combination of the sensible heat stored in the water and the latent heat stored inside the PCM capsules. The sensible heat stored by water is obtained from

$$Q_s = m_w \cdot C_p (T_f - T_i) \dots\dots\dots(2)$$

where m_w is the mass of water contained in the storage tank, while T_f and T_i denote the final and initial water temperatures, respectively.

The latent heat stored by the PCM during the melting process is expressed as

$$Q_L = m_{PCM} L \dots\dots\dots(3)$$

where m_{PCM} is the PCM mass and L is the latent heat of fusion.

Consequently, the total thermal energy stored within the storage system can be expressed as

$$Q_{Total} = Q_s + Q_L \dots\dots\dots(4)$$

The instantaneous thermal efficiency of the flat-plate solar collector was calculated according to

$$\eta = \frac{Q_u}{AI} \dots\dots\dots(5)$$

where A (m^2) is the collector area and I (W m^{-2}) is the incident solar irradiance.

The temperature evolution in each encapsulated module was continuously monitored during the charging period to evaluate the charging performance of the PCM. The melting characteristics were assessed by comparing the variation with time of the PCM temperature, the outlet water temperature and the storage tank temperature for the three encapsulation

materials investigated. Finally, the thermal performance of the aluminum, cast iron and stainless-steel capsules was comparatively evaluated under identical operating conditions. The comparison was based on the outlet water temperature, the PCM charging rate, the thermal response, the heat storage characteristics and the overall thermal efficiency of the storage system.

2.6 MEASUREMENT UNCERTAINTY ANALYSIS

To assess the reliability and accuracy of the obtained results, it is necessary to analyze the experimental uncertainty. The uncertainty of the calculated parameters in the present investigation was estimated by the root sum square (RSS) method proposed by Kline and McClintock and commonly used in thermal engineering experiments.

For a dependent variable R expressed as

$$R = f(x_1, x_2, x_3, \dots, x_n) \dots\dots\dots(6)$$

the combined uncertainty is determined as

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1} U_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} U_{x_2}\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} U_{x_n}\right)^2} \dots\dots\dots(7)$$

where

- U_R is the uncertainty of the calculated parameter,
- U_{x_i} is the uncertainty associated with each measured variable.

The total experimental uncertainty is a function of the uncertainties in the measurements of temperature, water flow rate, solar irradiance, and data acquisition. All measurements were recorded automatically with the SCADA system, thus human reading errors were greatly reduced, which improved measurement repeatability and experimental reliability.

The analysis of the experimental uncertainty confirms that the differences observed among the investigated encapsulation materials are significantly larger than the estimated experimental uncertainty, showing that the enhancements reported are statistically significant and can be attributed to the thermophysical properties of the encapsulation materials instead of measurement errors.

3. NUMERICAL MODEL

To complement the experimental investigation and provide a detailed understanding in this work, a three-dimensional transient numerical model was established to study the heat transfer characteristics inside the latent heat thermal energy storage (LHTES) system. The numerical simulation was used to predict the temperature distribution, melting and solidification behavior of the phase change material (PCM) and the thermal response of the different metallic encapsulation materials under the same operating conditions

as the experimental tests. The thermophysical properties of PCM and encapsulation materials were used to build the model and the experimental results were used as reference data for validation. The numerical model was based on the conservation equations of mass, momentum and energy. The governing equations were solved simultaneously to describe the transient heat transfer process during the charging and discharging of phase change material (PCM).

3.1 GOVERNING EQUATIONS

The continuity equation is expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad \dots\dots\dots(7)$$

where ρ is the density and $\mathbf{V}$ is the velocity vector.

The momentum equation is written as

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} + \rho \mathbf{g} + \mathbf{S} \dots\dots\dots(8)$$

where p denotes pressure, μ is the dynamic viscosity, $\mathbf{g}$ is the gravitational acceleration, and $\mathbf{S}$ represents the momentum source term associated with the phase change process.

The transient energy equation is given by

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + S_h \quad \dots\dots\dots(9)$$

where T is temperature, k is the thermal conductivity, and S_h represents the latent heat source term resulting from the melting and solidification of the PCM.

The enthalpy-permeability approach was used for the simulation of the PCM melting and freezing processes. According to this method, the mushy zone is represented as the porous material where permeability slowly reduces with the approaching value of liquid fraction to zero.

3.2 MODEL ASSUMPTIONS

In order to reduce the complexity of the numerical model without losing the important physical phenomena, the following assumptions were used:

1. The flow is three-dimensional, unsteady, and laminar.
2. The thermophysical properties of each material are homogenous and isotropic.
3. The PCM has a uniform initial temperature in the solid state.
4. The thermal contact resistance at the interface between the PCM and metallic casing was neglected.
5. The heat losses due to the insulated walls are neglected.

6. The radiative heat transfer in the storage tank was not considered.
7. The natural convection in the liquid PCM was considered by the buoyancy term using the Boussinesq approach

3.3 MATERIAL PROPERTIES

Properties of paraffin wax and the investigated metallic encapsulation materials were obtained from the literature and the manufacturers' data sheets. Properties such as density, thermal conductivity, specific heat capacity, latent heat of fusion, melting temperature range, and dynamic viscosity (for liquid PCM) were considered to be constant in the investigated temperature range.

3.4 BOUNDARY CONDITIONS

The boundary conditions used for the numerical simulation were chosen in order to mimic the real conditions existing in the experiments as closely as possible. The water temperature measured at the collector output was taken as the inlet boundary condition for the heat flow. The outside surface of the insulated storage tank was assumed to be an adiabatic boundary, while the convective heat transfer coefficient was assumed in the interface between the circulating water, metallic containers, and the phase change material. The initial temperature of the whole storage system was taken based on the measured temperature before starting the process of charging in experiments see Table 5.

Table-5: Numerical simulation parameters and boundary conditions.

Parameter	Value
Solver	Pressure-Based
Simulation Type	Transient
Flow Regime	Laminar
Gravity	9.81 m/s ²
Pressure-Velocity Coupling	SIMPLE
Pressure	Second Order
Momentum	Second Order Upwind
Energy	Second Order Upwind
Melting Model	Enthalpy-Porosity
Convergence	10 ⁻⁶ Energy, 10 ⁻⁴ Others
Initial Temperature	Experimental Value
Boundary Temperature	Experimental Collector Outlet

3.5 Mesh Independence Study

In order to make sure that the numerical results obtained from the calculations are independent of the computational grid, mesh independence study was carried out based on different structured and unstructured grids with gradually increasing number of computational elements. Outlet water temperature and average PCM temperature were chosen as the monitoring

parameters (see Table 6). The relative deviation from one refinement to another was carefully studied. Computational grid for which no change in predicted temperatures is observed while still keeping the computation time within reasonable limits was chosen for further computations.

Table 6. Mesh independence study

Mesh No.	Number of Elements	Outlet Temperature (°C)	Relative Error (%)
Mesh 1	92,436	51.73	—
Mesh 2	168,215	52.18	0.87
Mesh 3	284,637	52.46	0.53
Mesh 4	417,952	52.58	0.23
Mesh 5	603,184	52.69	0.21

3.6 MODEL VALIDATION

Model validation was performed based on the experimental data of the developed solar water heater test bench. Model validation has been done by comparison of the calculated and measured temperatures of the storage tank, PCM capsules, and collector exit point during the charging process. A good correlation was observed between the numerical simulation and the experimental results. This validates the developed model for its accurate representation of the performance of the latent heat thermal energy storage system. Any other differences might be due to the inherent errors of the experimental set-up, small heat losses, and assumptions made in the numerical simulation.

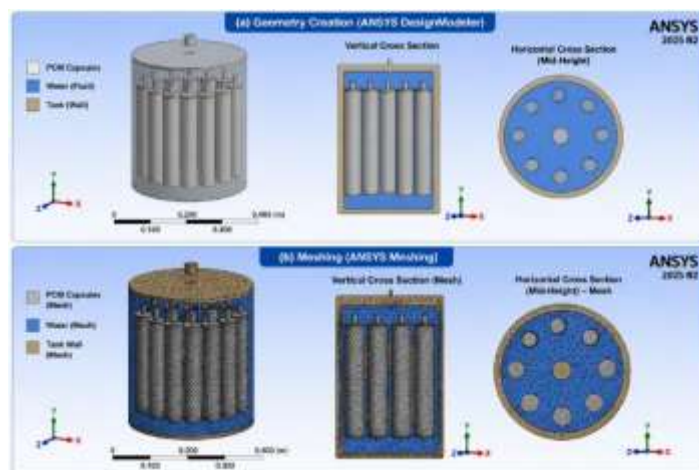


Figure 5. Numerical modelling procedure including the PCM capsule geometry, computational mesh, applied boundary conditions, and experimental validation of the ANSYS Fluent model.

4. RESULTS, VALIDATION, AND ENGINEERING DISCUSSION

4.1 EFFECT OF CAPSULE MATERIAL ON THERMAL PERFORMANCE

Four major parameters were employed to evaluate the thermal efficiency of LHTES system, i.e., collector thermal efficiency, total thermal energy stored, sensible heat storage, and latent heat storage, as illustrated in Figures 6-9. The encapsulation material had an evident effect on the charging performance of the PCM in terms of all performance parameters examined. As illustrated in Figure 6, collector thermal efficiency showed an increasing tendency during the morning time, peaked at around 14:00 and 15:00 h, and finally decreased with the decline in solar irradiance. The highest value of efficiency peak belonged to the aluminium, being 64.3%, followed by cast iron (61.4%) and stainless steel (57.0%). It could be explained by the considerably high thermal conductivity of aluminium, which resulted in reducing the conductive resistance of the capsule walls, leading to improving the convective heat transfer rate from water to the PCM. Therefore, thermal energy was transferred with higher efficiency to the storage media, and hence, a larger amount of solar radiation energy could be used. Such findings are in line with previously published results, indicating that better thermal conductivity of the capsule increases the performance of the PCM during the charging process [19-22].

The same phenomenon was seen in case of total thermal energy storage (Figure 7). In this regard, aluminium stores an energy of 4320 kJ, which is higher than that stored by cast iron (3990 kJ) and stainless steel (3600 kJ). The higher energy storage capacity in aluminium material can be attributed to the quick heat dissipation through the capsule wall, thus allowing a large volume of PCM to attain its melting point within the given time period. However, in the case of stainless steel, the lower heat dissipation capacity limited heat storage capacity.

The sensible heat storage findings (Figure 8) were relatively close since the initial charging process was dominated by the increase in temperature before the melting process took place. As the PCM temperature was getting closer to the phase transition point, the impact of the enclosure material became more apparent. This fact becomes clear from the latent heat storage results depicted in Figure 9, where aluminum managed to store the maximum latent heat (2200 kJ), followed by cast iron (1900 kJ) and stainless steel (1550 kJ). The differences in the findings show that increasing the thermal conductivity of the capsules speeds up the melting front propagation and makes the phase change more efficient.

In general, it can be observed from the above data that the thermal conductivity of the encapsulation material affects the performance of the latent heat thermal energy storage system through the regulation of heat transfer by conduction to the PCM. The higher the thermal conductivity of capsules, the lower the thermal resistance, the faster the diffusion of heat, and the better the exploitation of latent heat. Thus, the thermal efficiency and energy storage capacity of the solar water heater will increase. In addition, these results are confirmed by the CFD modeling discussed in the following sections.

4.2 TEMPERATURE EVOLUTION DURING THE CHARGING PROCESS

The transient variations of temperature difference between the collector outlet and inlet water ($\Delta T = T_o - T_i$) in the case of different PCM encapsulation materials have been shown in Figure 10. In all the cases, ΔT rose throughout the morning, had its maximum value between 13:00 and 14:00 h, and fell gradually in the late afternoon in consequence of the reduction in solar radiation intensity. Aluminium was seen to provide the highest ΔT among the three examined encapsulation materials, followed by cast iron and stainless steel. Higher values of ΔT in the case of aluminium mean better heat transfer from circulating water to encapsulated PCM due to which the thermal charging becomes faster and more efficient solar energy is used. The difference between the three encapsulation materials is clearly observed under conditions of maximum solar radiation intensity while their temperature values coincide at the beginning and end of the day due to lower thermal gradient.

In general, the findings clearly indicate that use of a high conductivity material in the encapsulation layer increases the heat transfer efficiency of the system during the charging cycle. This finding is in agreement with the previous works conducted for solar thermal energy storage systems using PCM [20-22].

4.3 NUMERICAL MODEL VALIDATION

The proposed three-dimensional CFD model was validated through comparison of outlet water temperatures predicted by the model against those experimentally measured at the same conditions. It can be seen from Fig. 11 that the numerical predictions matched the experimental data very well over the whole process of water charging, correctly capturing the transient behavior of the outlet water temperature. The ability of the model to predict the output temperature was estimated by calculating such statistical parameters as root mean square error (RMSE), mean absolute percentage error (MAPE), and the coefficient of determination (R^2). The model had RMSE = 0.82 °C, MAPE = 1.56%, and $R^2 = 0.991$, thus showing a high degree of agreement between the numerical and experimental data. The observed deviations can be explained by measurement errors, fluctuations in solar radiation in the course of outdoor experiments, and some simplifying assumptions made in modelling, such as constant properties of thermophysical media and ideal boundary conditions. However, these deviations were insignificant and did not affect the accuracy of the numerical model.

In summary, the validation clearly indicates that the ANSYS Fluent model developed is an accurate representation of the transient behavior of the latent heat thermal energy storage system with phase change material. Therefore, the validated model can be used in parametric studies in the future without having to conduct a lot of experiments.

4.4 Heat Transfer Characteristics and Temperature Distribution

Figures 12(a-c) below show the contours of transient temperatures obtained using the ANSYS Fluent model of the aluminum, cast iron, and stainless-steel capsules respectively during the process of PCM charging. The numerical analysis gives clear insight about the heat transfer and melting characteristics of the PCM, and the results are comparable to those obtained from experiments. In the case of the aluminium capsule (Figure 12a), the temperatures were fairly uniform, and thermal gradients were low. Its higher thermal conductivity facilitated faster diffusion of the heat through its walls, which helped achieve faster melting and a more uniform thermal field in the PCM. This, in turn, allowed more effective heat transfer, which is reflected in the increase in thermal efficiency and energy storage.

However, the calculated temperature profile proves that there was enough melting in case of the charged container, corroborating the average experimental performance of the latter. At the same time, the stainless-steel capsule (Figure 12(c)) displayed the highest temperature gradients and lowest heat penetration rate. Poorer thermal conductivity of stainless steel caused an increase in conductive resistance through the wall of the capsule, thus slowing down the movement of the melting boundary and hindering the process of PCM melting for the given amount of time. As a result, a relatively small amount of the PCM participated in latent heat storage.

Generally, the results of computations show that the thermal conductivity of the material used for encapsulation is the main parameter which defines the rate of heat diffusion and melting processes inside the PCM. Better thermal conductivity means higher heat transfer rates, lower thermal resistance, and consequently improved performance of charging process. Perfect match between computed and experimental data also proves the high accuracy of the validated CFD model in simulation of the PCM transient melting process.

4.5 ENGINEERING IMPLICATIONS

The results obtained in the present study prove that the choice of PCM encapsulation material is an important design parameter in latent heat thermal energy storage system, as opposed to just a structural one. As can be seen from the obtained results, the higher thermal conductivity of the capsule means better heat transfer to PCM, faster melting, and improved charging performance in general. Of all the tested materials, aluminum turned out to be the most responsive to temperature because of its high thermal conductivity. This material showed the highest thermal efficiency, energy storage, and fast charging rate. Therefore, aluminum is a more preferable material for solar water heating systems which require fast energy storage and efficient use of the available energy. On the other hand, cast iron provides a good balance between thermal performance and mechanical strength, while stainless steel is less suitable because of low thermal conductivity. This is a very useful way to evaluate various possibilities related to the encapsulation material selection in order to optimize the PCM energy storage system without relying much on experimental analysis. In addition, the present modeling strategy could be further used for analyzing

the performance of advanced techniques for thermal enhancement such as composite PCMs, nano-enhanced PCMs, metallic foams, finned capsules, etc.

Thus, the entire experimental-numerical framework developed in this work could be effectively applied in the design and optimization of PCM based solar energy storage systems.

It should be noted that the present conclusions are limited to the investigated paraffin PCM and operating conditions; different PCMs or charging rates may alter the relative performance of the encapsulation materials.

Table 7 compares the present study with representative literature on PCM-based solar water heating systems, highlighting the research gap and the main methodological and engineering contributions of the proposed experimental-numerical approach. The observed trend agrees with the findings reported by Reddy et al. [19], who also identified capsule thermal conductivity as an important factor governing PCM charging, although the present study achieved higher thermal efficiency owing to the use of a controlled experimental platform and identical operating conditions.

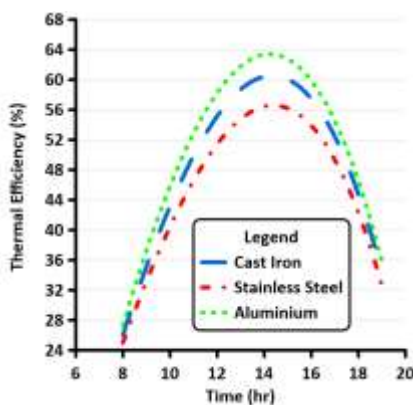


Fig-6. Thermal Efficiency (%) for the Three Capsule Materials

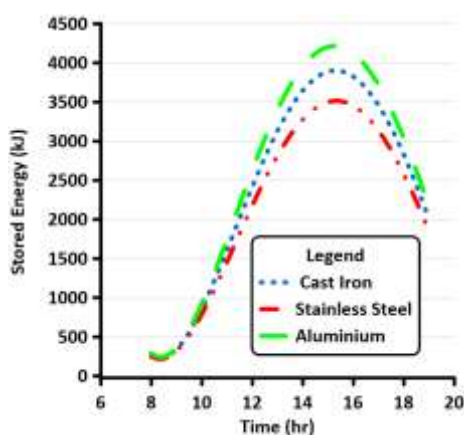


Fig-7. Stored Energy (kJ) for the Three Capsule Materials

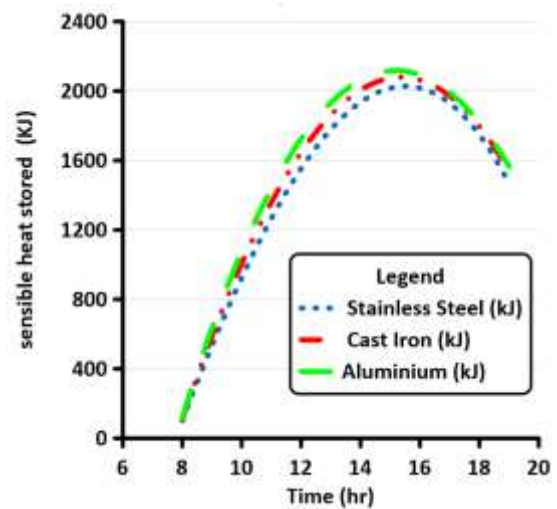


Fig-8. Hourly sensible heat stored in the PCM system for different capsule materials during the charging period

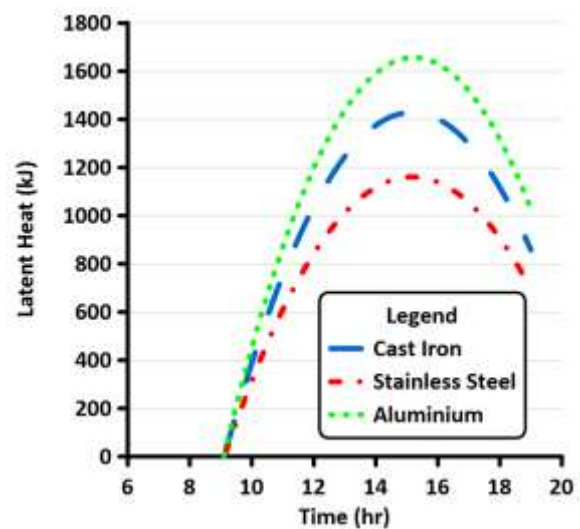


Fig-9 . Latent Heat (kJ) system for different capsule materials during the charging period

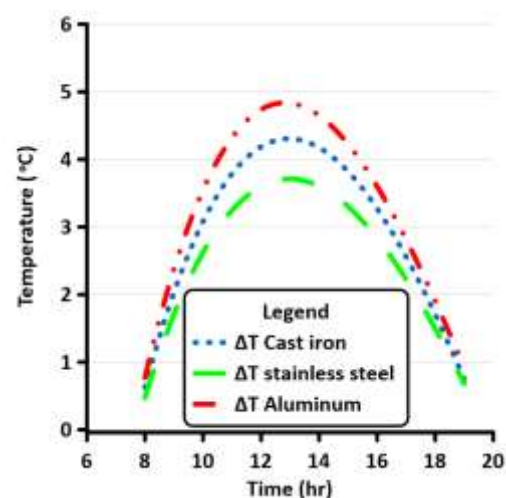


Fig-10. Hourly variation of water temperature difference (ΔT) for aluminum, cast iron, and stainless steel PCM capsules during the charging process.

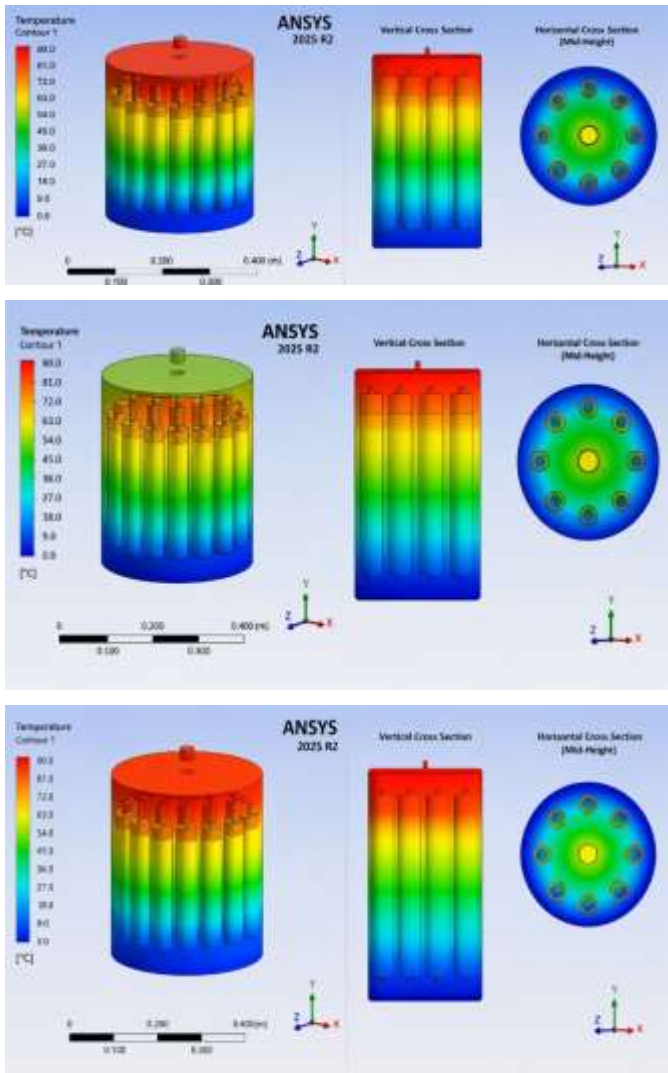


Fig-12. Temperature contours predicted by ANSYS Fluent during the charging process for different PCM encapsulation materials: (a) aluminum, (b) cast iron, and (c) stainless steel.

Table-7: Comparison of representative studies on PCM-based solar water heating systems and the research gap addressed in the present work.

Refer ence	Research Focus	PCM / System	Main Findings	Limitations	Contribution of the Present Study
Reddy et al. [19]	Effect of capsule material	Paraffin in Al, mild steel and HDPE capsules	Capsule material had limited influence on charging/discharging	Simplified setup and limited instrumentation	Standardized experimental platform with comprehensive instrumentation and numerical validation
Asif et al. [20]	Solar collector material	Aluminium vs stainless-steel	Aluminium improved collector efficiency	No PCM or latent heat storage	Evaluates metallic capsule materials

Refer ence	Research Focus	PCM / System	Main Findings	Limitations	Contribution of the Present Study
		collector			in PCM-based storage
Nadji b et al. [21]	Capsule arrangement	Paraffin capsules	Improved thermal stratification	Same capsule material	Investigates influence of capsule material under identical operating conditions
Patel and Rathod [22]	Capsule geometry	RT60 PCM	Geometry enhanced storage performance	Capsule material not investigated	Isolates the effect of metallic encapsulation materials
Ahmed et al. [9–13]	Heat transfer enhancement	PV/Trombe systems	Improved thermal performance using porous media	Not focused on PCM encapsulation	Focuses on encapsulation material as the governing parameter
Aljumaily et al. [14–17]	Heat exchanger optimization	LHTES systems	Faster charging/discharging	Different system configurations	Develops validated experimental-numerical framework
Present Study	Metallic encapsulation materials	Paraffin in aluminium, cast iron and stainless-steel capsules	Combined experimental and CFD investigation under identical operating conditions	—	Standardized experimental methodology, SCADA monitoring, validated 3D CFD model, and engineering recommendations

5. CONCLUSIONS

The current work experimentally and numerically examined the effect of the metal material used for the encapsulation of the latent heat thermal energy storage made of paraffin wax and incorporated in the forced-circulation solar water heating system. Based on the findings obtained, the following conclusions can be drawn:

1. Charging behaviour of the PCM system was highly affected by the encapsulation material.

The higher thermal conductivity of the material decreased conductive thermal resistance, increased heat transfer, and caused the faster PCM melting process.

2. Aluminium performed the best thermal behaviour compared with the studied materials and reached the highest values of thermal efficiency of the collector (64.3%), stored thermal energy (4320 kJ), and latent heat storage (2200 kJ) due to high thermal conductivity of aluminium.
3. Cast iron had moderate thermal properties while stainless steel had the lowest values of charging efficiency due to low thermal conductivity of the material and lower heat penetration in the encapsulant.
4. The developed 3D CFD model effectively predicted the transient thermal behaviour of the system with a good correlation with experimental data (RMSE = 0.82 °C, MAPE = 1.56%, $R^2 = 0.991$).
5. This method of analysis is a robust approach to analyze the encapsulation materials and improve the efficiency of solar thermal energy storage based on PCMs without requiring excessive experimental tests.

Future research directions can include studying the cyclic behavior of PCMs over an extended period of time, analyzing the techno-economic performance of various other encapsulating materials, and employing advanced heat transfer augmentation methods such as composite PCMs and metallic foams.

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