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Analysis of Heat Transfer in the Energy Storage during Solidification Period

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ABSTRACT

Energy storage is an important factor in improving energy efficiency especially in the residential use. Thermal Energy Storage (TES) systems employ Phase Change Materials (PCMs), including paraffin. However, prior research fails to capture the impact of the number of PCM balls on heat transfer rate, solidification, and pressure drop. This study fills this gap by investigating the effect of different TES tank configurations with different sizes of paraffin balls in solidification conditions. This study aims to analyse heat transfer in thermal energy storage tanks under solidification conditions. This involves developing storage tanks with three different numbers of paraffin balls: 4, 6, and 8 balls) in the TES tank. The tanks were designed for residential use, and the analysis utilised Computational Fluid Dynamics (CFD) approaches to evaluate heat transfer. The findings showed that the heat transfer rate and temperature distribution were improved when the TES tank contained more paraffin balls. Tanks with 8 paraffin balls took 25% less time to cool as compared to tanks with 4 balls because of the greater surface area for heat transfer. The temperature of the balls in the 8-ball tank reduced uniformly and the temperature variation was 15% more uniform than the one in the 4-ball configuration. In pressure drop, it was observed that the tanks with fewer paraffin balls had a higher pressure drop by 20% which shows that the fluid is moving faster but at the same time the stability is low. Tanks with 8 balls were less fluctuating in pressure which is important for energy storage as compared to the tanks with 4 balls. Based on these findings, it is suggested to use a TES tank with a larger number of paraffin balls to improve total heat transfer rate and temperature uniformity in residential applications.

1. Introduction

Energy storage technology is widely used in air conditioning, distributed energy systems, solar energy systems, and waste heat recovery systems [1]. It significantly reduces operational expenses,

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boosts system stability, and increases energy efficiency [2]. Thermal energy storage (TES) units are primarily used to store heat or cold that can be used later or stored under various power, temperature, and other conditions. Compared to other storage types, TESs are more affordable and have very simple working principles and structures [3].

Thermal energy storage systems play a critical role in smoothly integrating renewable energy sources into the power grid and reducing the increasing bottlenecks caused by fluctuations in energy demand. Among the ever-growing global energy demand, a firm grasp of efficient and sustainable energy management solutions has emerged [4]. Building energy efficiency and energy demand can be increased with the help of TES technology [5]. TES technology can benefit various sectors, including residential [6-8], industrial [9,10], and power generation [11,12].

There are three primary types of thermal energy storage: latent heat, sensible heat, and thermochemical [13]. In this study, Latent Heat Thermal Energy Storage (LHTES) is used where this type of storage occurs due to the phase change in which the solid-liquid phase change occurs. Energy is released during solidification and stored during melting of the material [3]. Phase change materials (PCMs) are used as energy storage media in LHTES systems and are excellent at storing large amounts of thermal energy at nearly constant temperatures [14].

PCM is a substance that releases or stores thermal energy when it undergoes a phase transition from solid to liquid, or vice versa. As a result of this characteristic of PCMs, electrical energy utilised for operating HVAC systems can be stored as latent thermal energy in TES tanks, which are composed of a heat transfer fluid (HTF) and PCM [5]. PCM can be used to close the supply-demand gap while also enhancing the system's energy efficiency [15]. Therefore, PCM with large latent heat capacities is essential for TES. The material reduced the operating temperature of the condenser during the day by absorbing thermal energy from an incoming air mass inlet to the condenser. At night, energy is released into the incoming air mass, providing preheating for the condenser [16]. PCMs can be classified depending on their thermal performance, including phase-change temperature and latent heat [17]. There are three primary classes of phase change materials: organic, inorganic, and eutectic PCMs [18].

Thirumaniraj *et al.,* [19] conducted experimental and numerical studies on TES using paraffin wax as PCM. This study focuses on the design and analysis of a thermal energy storage (TES) system using paraffin wax as a phase change material (PCM) for efficient solar energy utilisation. Stainless steel was chosen for the TES tank and spherical balls due to its corrosion resistance and strength. Paraffin wax with a melting point of 40-43°C was selected as the PCM because of its heat-trapping capacity and chemical stability. A stainless-steel tank was designed with dimensions of 400 mm in height and 220 mm in diameter. The sample contained 72 spherical stainless-steel balls filled with paraffin wax, which were arranged in six rows. The study also includes a computational analysis using ANSYS Fluent, which models the TES tank and provides the temperature and pressure contours during charging and discharging.

Surya *et al.,* [14] conducted experiments to evaluate the performance of an LHTES system using PCM-filled spherical balls with and without solid internal fins. The PCM was paraffin, which had a melting point of 61℃, and the heat transfer fluid (HTF) was water, which was maintained at a constant temperature of 70℃. For various HTF flow rates, the temperature fluctuations of the HTF and PCM over time were studied. Additionally, research has been done on the impact of non-dimensional numbers like Reynolds, Rayleigh, Nusselt, and Stanton numbers. The performance parameters, including entropy generation and thermodynamic efficiency. The goal of heat storage is to achieve a highly efficient arrangement to accumulate the most energy and achieve higher energy efficiencies during the charging process.

In the research conducted by Dong *et al.,* the temperature variance and phase transition process of a single PCM ball were measured experimentally. A physical model of a PCM ball was created using the CFD simulation software and was verified against the experimental results. The thermal performance of a cold energy storage tank containing PCM balls was then simulated using this verified model. The study assessed the effects of variables including the chilled water flow rate in the tank and the PCM ball diameters (90 mm, 90 mm & 60 mm, and 60 mm). These findings show that smaller ball diameters and faster chilled water flow rates can result in a greater PCM ball freezing rate [1].

Previous studies have demonstrated that a consistent effective thermal conductivity throughout the melting process can be used to define natural convection in PCMs. However, Amin *et al.,* ignored the impact of greater buoyancy forces on the temperature difference between the heat transfer fluid surrounding the encapsulation and the PCM. The heat transfer through a single sphere under various temperature differentials was experimentally investigated. A CFD model was created that neglected the PCM's buoyancy inside a sphere. Using this CFD model, data from the model were correlated against experimental data at different temperature differences with water as the PCM to establish the effective thermal conductivity of the liquid part of the PCM. As a function of Rayleigh number, an appropriate relationship for effective thermal conductivity was established. The geometry and PCM employed in this investigation are covered by this empirical correlation. This research shows how effective thermal conductivity relationships can be used to simulate natural convection in PCM thermal storage devices [20].

This study addresses the gap in understanding how the number of PCM balls, specifically paraffin, affects heat transfer during the solidification process in TES systems. Previous research often focuses on PCM materials without examining the impact of varying quantities of PCM balls within the tank. This study aims to analyse heat transfer in thermal energy storage tanks under solidification conditions. This involves developing storage tanks with three different numbers of Paraffin balls: 4, 6, and 8 balls) in the TES tank. The tanks were designed for residential use, and the analysis will use Computational Fluid Dynamics (CFD) approaches to evaluate heat transfer in the tank. This comprehensive investigation seeks to optimise the configuration and operation of PCM-based thermal energy storage systems for residential applications.

2. Methodology

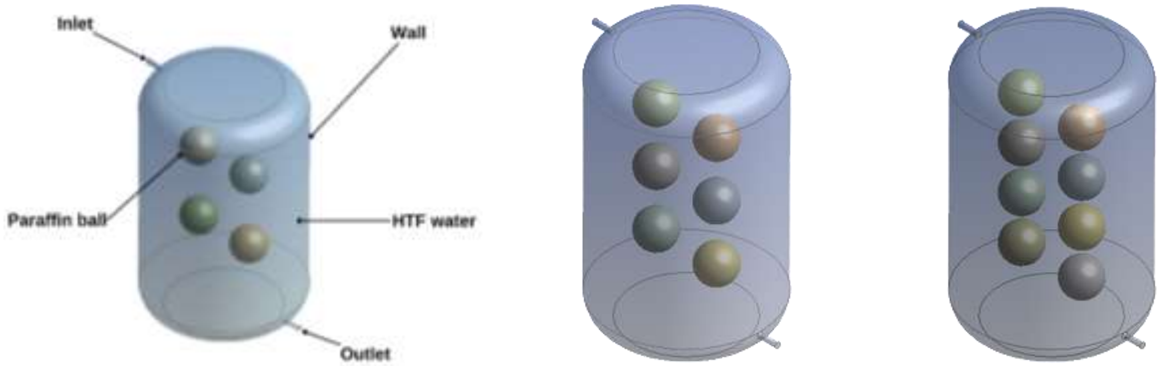
This methodology explained in detail the steps and procedures involved in the simulation via ANSYS Fluent software (Canonsburg, Pennsylvania, USA) to analyse the heat transfer in thermal energy storage during solidification.

2.1 Geometry of PCM Ball Numbers

The encapsulated PCM spheres in the tank filled with HTF was modelled using the computer aided design software called ANSYS Design Modeler. Three tanks with varying numbers of paraffin balls (4, 6, and 8 balls) were created and simulated in this study. The tank is illustrated in three dimensions in Figure 1. The tank comprises the following four parts: a body, paraffin balls, an inlet pipe, and an output pipe. Table 1 lists the dimensions of the PCM balls and TES tank.

Table 1
Dimensions of the PCM balls and TES tank [14]

Parameter	Value (cm)
Ball diameter	7.62
Diameter of the TES tank	33
Height of the TES tank	51
Pipe diameter	1.2
Pipe length	5



(a) (b) c)

Fig. 1. The geometry of the TES tank (a) 4 paraffin balls (b) 6 paraffin balls (c) 8 paraffin balls

2.2 Discretization of the TES Tank

In performing numerical analysis, discretization is an essential step. Discretization is the process of dividing a continuous domain into a finite number of control volumes or elements. The discretization technique used in this simulation involved meshing, governing equations, boundary conditions, and parameter assumptions.

2.2.1 Meshing of PCM balls in TES tank

Mesh size affects the accuracy of the simulation results, with a finer mesh generally yielding more precise outcomes. However, a finer mesh requires more computational resources and processing time [21]. The ideal mesh size was determined for a single encapsulated PCM in thermal storage, and it was discovered that the mesh with the lowest aspect ratio produced uniform tabulated tetrahedral elements that satisfied 0.85 of the maximum skewness [20]. The fluid domains of the spherical PCM ball and cylindrical tank were created using tetrahedral mesh shapes with an average skewness of 0.80. Figure 2 illustrates a cross-section of the mesh model of the TES tank containing PCM balls. The full-scale model, consisting of 80 257, 85 662, and 90034 nodes for tanks 1, 2, and 3, respectively, with the same element size of 7 mm was utilised in all simulations.

Fig. 2. The section view of the meshed model

2.2.2 Governing equations

In this study, the governing equations for continuity, momentum, and energy were solved simultaneously. In addition to terms that handle the liquid-to-solid phase transition, these equations consider the conservation of mass, momentum, and energy. The equations are obtained from the previous study [22-26].

In this study, the fluid is considered incompressible, resulting in the constant of fluid density throughout the flow field. Thus, the continuity equation can be written as in Eq. (1):

$$\nabla \cdot V = 0 \tag{1}$$

Eq. (2) represents the conservation of momentum, accounting for the forces acting on the fluid within the TES tank. It describes how the velocity of the fluid changes over time due to pressure gradients, viscous forces, gravity, and any additional source terms related to phase change and can be expressed as:

$$\frac{\partial \rho \mathrm{V}}{\partial \mathrm{t}} + \nabla \cdot (\rho \mathrm{V}) = -\nabla \mathrm{P} + \mu \nabla^2 \mathrm{V} + \rho \mathrm{g} + S_v \tag{2}$$

Eq. (3) describes energy conservation within the system, specifically accounting for heat transfer in the TES tank. It includes the enthalpy transport due to fluid motion, conduction, and additional heat sources such as those associated with phase change. The energy equation can be represented as:

$$\frac{\partial \rho \mathrm{H}}{\partial \mathrm{t}} + \nabla \cdot (\rho \mathrm{VH}) = \nabla \cdot (k \nabla T) + S_H \tag{3}$$

where ∇ is the divergence operator, V is the velocity ρ is the density, P is the pressure, μ is the dynamic viscosity, g is the gravitational acceleration, S_v is the momentum equation source term, H is the total enthalpy, k is the thermal conductivity of the PCM, T is the temperature, and S_H is the energy equation source term.

2.2.3 Boundary conditions and parameter assumptions

Two primary domains were identified in this study: PCM and HTF. Paraffin as the PCM and water as the HTF were used in this study. Table 2 lists the properties of the HTF and Paraffin balls. The PCM balls were placed at the centre of the cylindrical tank, evenly spaced from each other. The boundary conditions applied are as follows: the inlet velocity is set at 0.01 m/s at a temperature of -5 ℃. The outlet temperature is set to 0°C, aligning with a previous study that indicates a temperature range of 0 to 5°C [5]. The outlet pressure is maintained at 0 Pa gauge pressure because the outlet is exposed to atmospheric conditions, meaning there is no pressure differential to drive flow at this boundary. The initial temperature of the paraffin balls is -8 ℃. The inlet velocity and outlet pressures were obtained from past study [15].

Table 2
Properties of HTF and Paraffin [14,27,28]

Properties	Water	Paraffin
Density, ρ (kg/m^3)	998.2	670
Specific Heat, c_p (j/kg·k)	4182	2400
Thermal conductivity k (W/m·k)	0.6	0.4
Viscosity (kg/m· s)	0.0010003	0.0269
Pure-solvent melting heat (j/kg)	19800	213000
Solidus Temperature (℃)	0	61
Liquidus Temperature (℃)	0	61

The simulation used several models, including the energy equation, the k-epsilon viscous model, and the solidification–melting model. It operates with a pressure-based solver in a transient state to capture time-dependent changes. The SIMPLE method was used to solve the equations and ensure accurate pressure calculations. The default settings were used for the solution controls, and all residuals were set to 0.0001 for precise results. The following assumptions were made for the entire tank:

i) Incompressible fluid, whose density remains constant during flow.
ii) Inviscid flow so we can neglect the effect of viscosity and shearing stresses.
iii) No roughness at the wall, resulting in no slippage.

2.3 *Grid Independence Test*

In CFD, the Grid Independency Test (GIT) was used to find the ideal grid resolution for numerical simulations. The purpose of this test is to verify that the simulation results are correct and dependable regardless of the grid resolution [29]. A grid independence test was performed with seven different numbers of nodes ranging from 15000 to 290000 nodes. The temperature distribution along a paraffin ball is plotted. As a result, to reduce the computational time, GIT 4, with element sizes of 7 mm, was selected in the simulation because the percentage of normalised error was less than 5%. Figure 3 shows the GIT of the simulation.

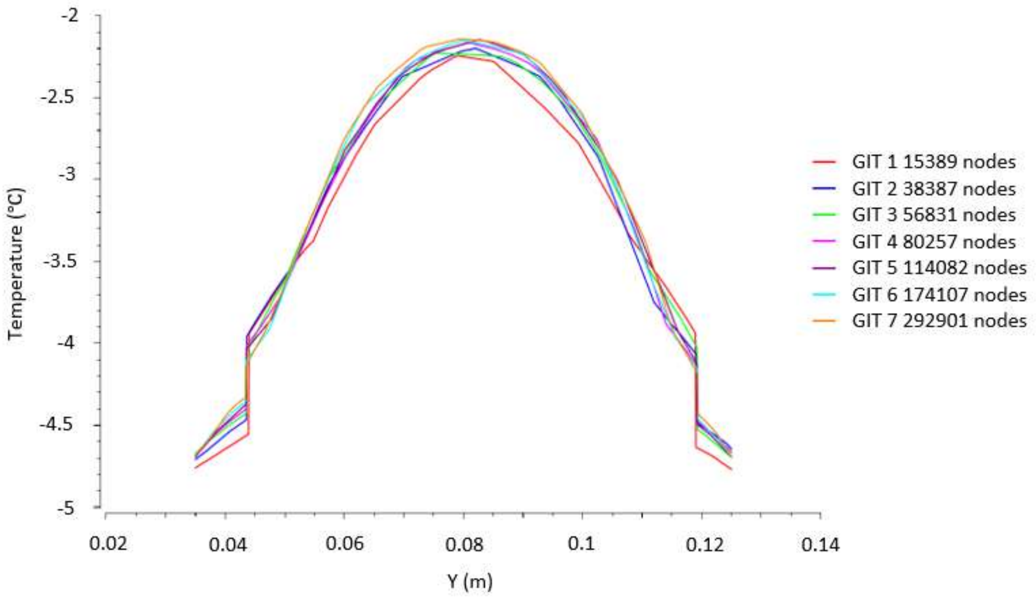


Fig. 3. GIT of thermal energy storage

3. Results

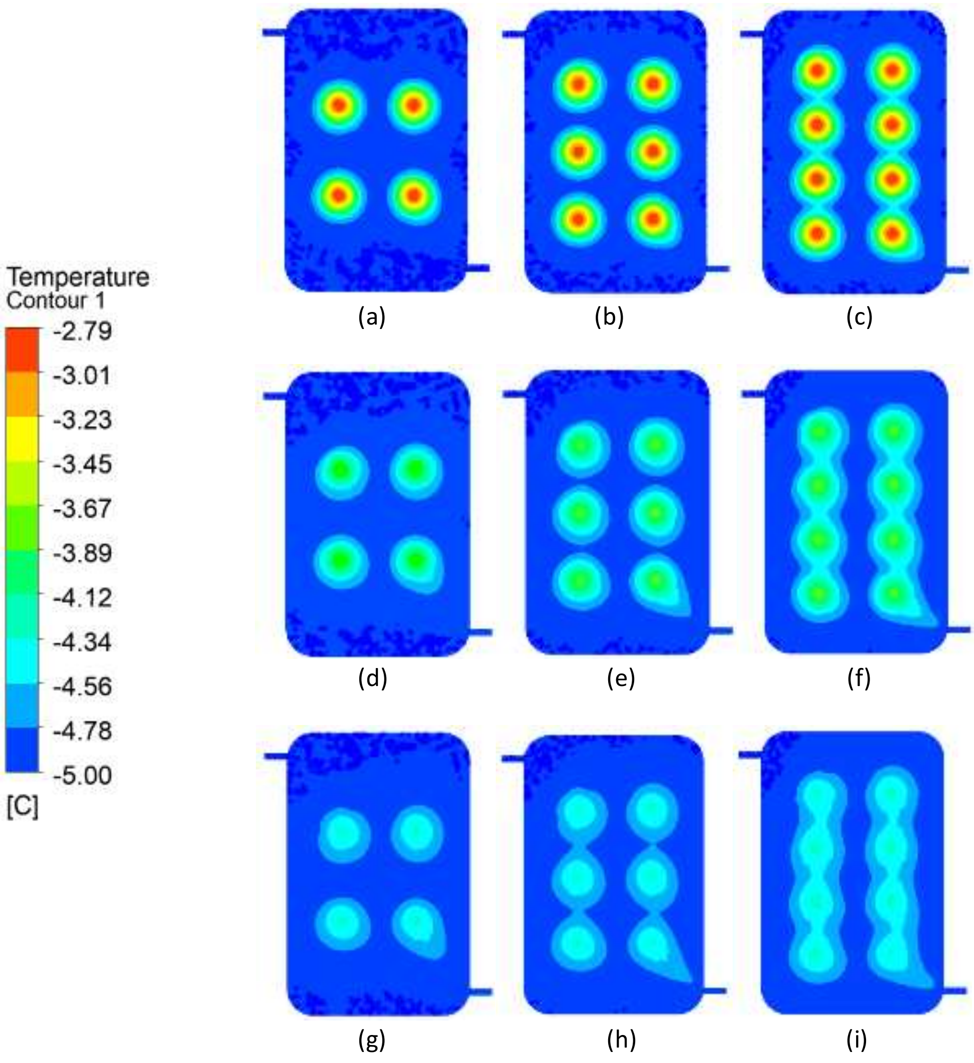
This section presents a comprehensive analysis of the thermal behaviour of paraffin balls within the TES tank, focusing on key parameters such as temperature distribution, pressure drop, and total heat transfer rate. These details are shown using contour plots and graphs, visually representing how heat is transferred and distributed throughout the tank over time.

3.1 Temperature Distribution in the TES Tank

The temperature distribution within the tank varied as the paraffin balls solidified and released latent heat. Due to constant heat loss by conduction and convection as well as the release of latent heat during solidification, the temperature of paraffin balls decreases with time. The temperature of the paraffin balls quickly decreased as the number of paraffin balls inside the tank increased. This occurs because of an increase in the total surface area for heat transfer. As each paraffin ball released internal heat to the surrounding fluid more quickly, the high heat transfer rate caused the temperature of the balls to drop more rapidly.

The temperature distribution contours shown in Figure 4 illustrate the temperature distribution of the paraffin balls within the TES tank. As the solidification process progresses, the quantity of paraffin balls inside the TES tank has a significant influence on the overall temperature distribution within the tank as the solidification process progresses. The overlapping cooling regions visible in the contours as the number of paraffin balls increases show that the balls' proximity improves the overall heat transfer rate by generating more interfaces for thermal energy exchange with the surrounding fluid. This greater heat dissipation causes a more rapid and uniform temperature drop over the tank. Furthermore, the contours demonstrate that the solidification begins at the surface of the paraffin balls and gradually moves inward. The temperature gradient observed at the walls and centre of each ball emphasizes the significance of thermal conduction as the primary heat transfer mechanism during the initial phase of solidification, with convection improving the overall cooling effect as solidification continues.

Figure 4 represents how the temperature changes for different numbers of paraffin balls in the TES tank over time, providing insights into how the cooling and solidification processes evolve. At 10 min, cooling was focused on each of the 4 paraffin balls, the cooling effect is more localized, resulting in a marked temperature difference between the wall and the centre of each paraffin ball, where the outer regions are cooler compared to the central area. As the number of paraffin balls increases to 6 and 8 balls, the cooling effect was broader and overlapping. There are red regions in the centre of the tank 2.79°C, showing where the paraffin has not solidified. The paraffin ball releases thermal energy over time, resulting in a decrease in the temperature. In 20 minutes, the red region turns green, which indicates that the temperature has become cooler and the paraffin balls continue to release the thermal energy. At 30 min, the green spots become smaller, and the blue region starts to spread evenly, indicating that paraffin starts to solidify. At 40 and 50 min, we can see that the temperature evens out more, with most of the tank getting cooler, indicating that solidification is almost complete. This pattern demonstrates how adding more paraffin balls to the tank improves its efficiency and consistency. Overall, the temperature differences decreased, and the tank's temperature became more uniform, showing how solidification progressed from the centre to the wall of the ball.



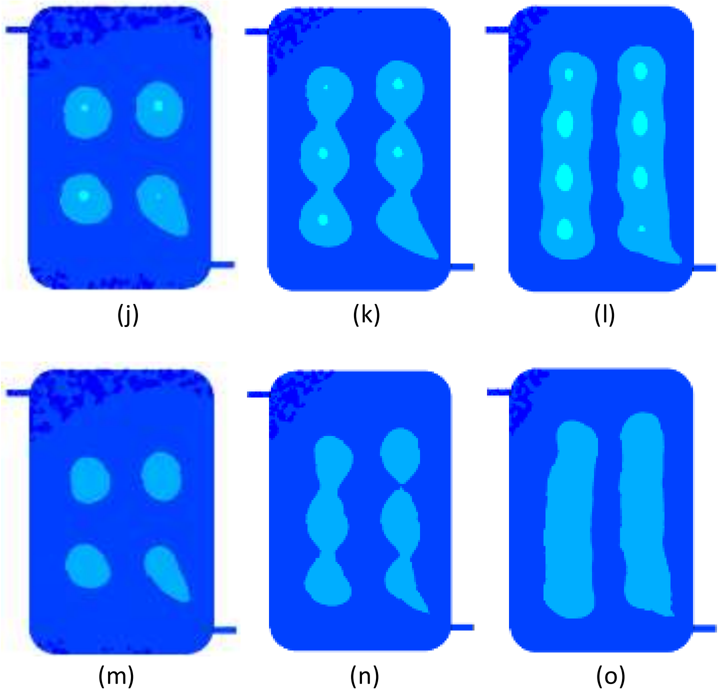


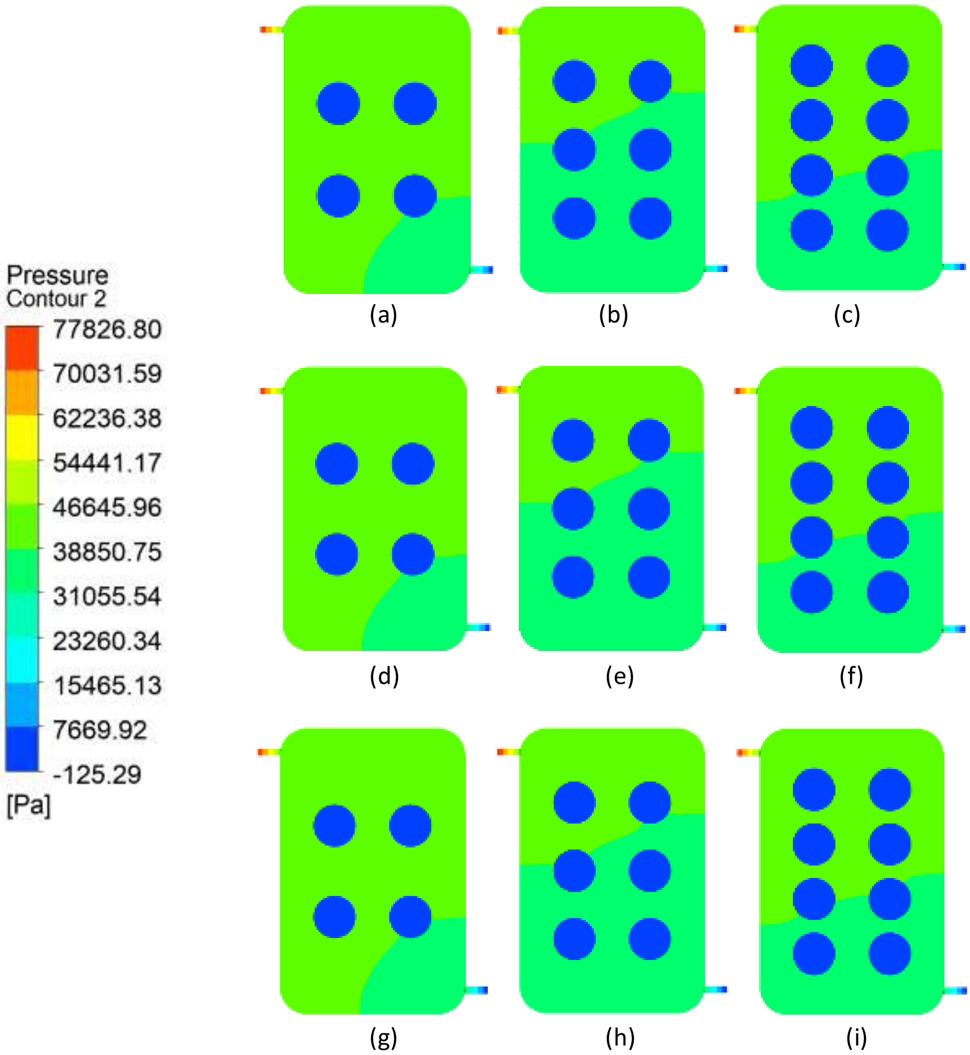
Fig. 4. Distribution of the temperature in TES tank (a) 4 paraffin balls (b) 6 paraffin balls (c) 8 paraffin balls during 10 minutes, (d) 4 paraffin balls (e) 6 paraffin balls (f) 8 paraffin balls during 20 minutes, (g) 4 paraffin balls (h) 6 paraffin balls (i) 8 paraffin balls during 30 minutes, (j) 4 paraffin balls (k) 6 paraffin balls (l) 8 paraffin balls during 40 minutes, and (m) 4 paraffin balls (n) 6 paraffin balls (o) 8 paraffin balls during 50 minutes

3.2 Pressure Drop in the TES Tank

Figure 5 illustrates the pressure drop in three tanks containing different numbers of paraffin balls. The findings indicate a significant difference in the pressure between the inlet and outlet of the tank due to the height difference. The pressure difference was more noticeable in a tank with fewer paraffin balls. When the TES tank contains fewer paraffin balls, the pressure difference between the inlet and outlet increases because the fluid flows more readily and quickly through the tank with less resistance. Consequently, there is an increase in fluid velocity, which increases the pressure loss from the inlet to the outlet. This increased pressure loss is attributed to the fact that the fluid encounters less obstruction in a less densely packed tank, leading to a more substantial pressure drop as the fluid flows from a higher to a lower point due to the height differential. The effect is compounded by the relationship between fluid velocity and pressure drop; as the velocity of the fluid increases, so does the pressure drop associated with overcoming the height difference within the tank. Tanks with more paraffin balls, on the other hand, provide more flow resistance, slowing down fluid movement and lowering overall pressure loss.

According to the contour, the pressure distribution in the paraffin balls was constant even though the time was increasing as a result of the phase change occurring at relatively constant temperatures. This characteristic is essential for the stability and efficiency of the energy storage and release process in the system. The consistent pressure measured at the paraffin balls in the TES tank while solidifying indicates that the pressure inside the tank remained constant and constant without significant changes. When paraffin is solid, it is typically unable to be compressed and retains both its volume and shape. This steadiness prevents major pressure fluctuations near the paraffin balls. Because paraffin remained solid during the simulation, any potential phase transition from solid to liquid, which usually leads to pressure changes due to volume expansion or contraction when the substance melts or solidifies, did not occur. Because of the pressure distribution's stability, there is less chance of pressure-induced variations affecting the thermal energy storage system's dependability and overall performance. Sustaining this level of steady pressure is necessary to maximise heat transfer efficiency and guarantee steady and predictable energy storage and release.

Moreover, the overall thermal performance of the TES tank is influenced by the stability of pressure within the paraffin balls. The constant pressure guarantees reliable and predictable thermal energy storage and release since it shows that pressure variations do not affect the heat transfer properties inside the tank. In order to minimise thermal losses and maximise heat transfer rate, the PCM maintains a stable operating environment, which can result in more effective energy storage. Furthermore, the absence of significant pressure fluctuations reduces the risk of mechanical stress on the tank and associated components, further enhancing the system's durability and longevity. Thus, the steady pressure distribution observed with solid paraffin is essential to preserving the effectiveness and dependability of the TES system.



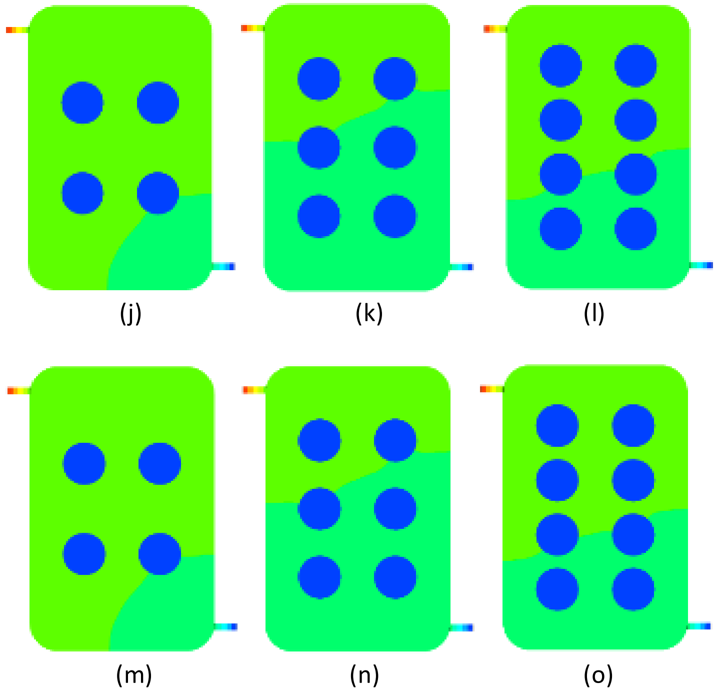


Fig. 5. Distribution of the pressure drop in TES tank (a) 4 paraffin balls (b) 6 paraffin balls (c) 8 paraffin balls during 10 minutes, (d) 4 paraffin balls (e) 6 paraffin balls (f) 8 paraffin balls during 20 minutes, (g) 4 paraffin balls (h) 6 paraffin balls (i) 8 paraffin balls during 30 minutes, (j) 4 paraffin balls (k) 6 paraffin balls (l) 8 paraffin balls during 40 minutes, and (m) 4 paraffin balls (n) 6 paraffin balls (o) 8 paraffin balls during 50 minutes

3.3 *Heat Transfer Rate of Paraffin Balls*

Paraffin balls transfer heat mainly through conduction and convection during solidification [30]. Latent heat is emitted to the surroundings when paraffin inside the ball hardens. As the paraffin ball gradually loses thermal energy, the released heat increases the temperature of water, contributing to the solidification process inside the ball. Increasing the number of paraffin balls in the TES tank improved the overall heat transfer rate. This is because adding more balls increases the surface area for heat exchange and the overall capacity for storing and releasing thermal energy. The heat transfer rate is also dependent on time. At the beginning of the simulation, the heat transfer rate is typically higher as the temperature difference between the heat transfer fluid and the paraffin balls is greater, leading to more rapid heat exchange. Over time, as the paraffin balls approach thermal equilibrium with the surrounding fluid, the heat transfer rate decreases. This result was due to the reduction in the temperature gradient between the balls and fluid. The graph of the total heat transfer rate for each reaction against time is plotted in Figure 6.

The figure shows the changes of total heat transfer rate over time for three TES tanks containing 4, 6, and 8 paraffin balls. Initially, within the first 10 minutes, tank 2 exhibited the highest heat transfer rate, followed by tank 3, and then tank 1. This means that the presence of more paraffin balls leads to a higher heat transfer rate. However, as time went on from 10 to 20 minutes, the heat transfer rates for all tanks significantly decreased. By 20 to 30 minutes, the rates for tank 2 and 3 balls are similar. From 30 to 50 minutes, the heat transfer rates for all tanks are almost identical, indicating that the number of balls has less impact as the system reaches thermal equilibrium. In summary, more paraffin balls increased the initial heat transfer rate, but this effect decreased over time, leading to similar rates for all tanks in the end.

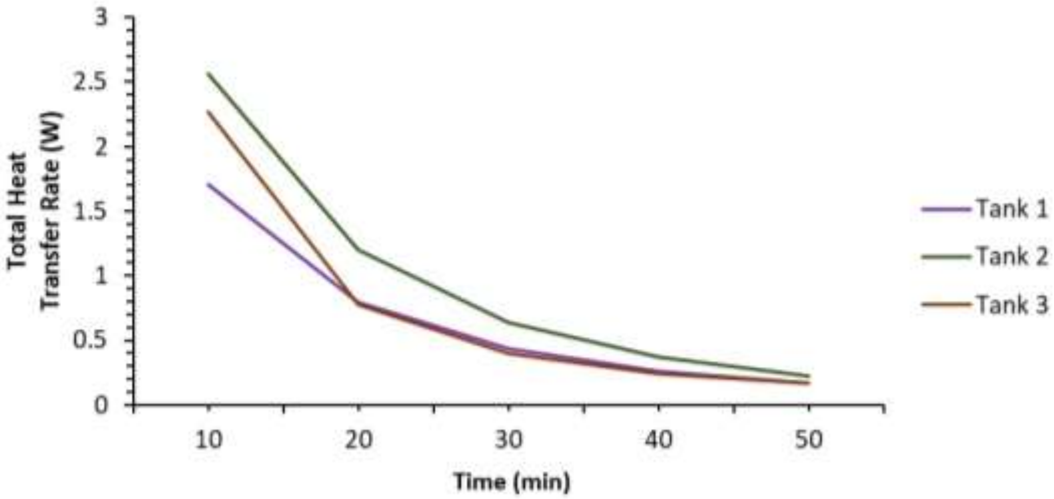


Fig. 6. Total heat transfer rate

4. Conclusions

The results of the simulation show that the temperature distribution and total heat transfer rate are significantly affected by the number of paraffin balls present in the TES tank. As the number of paraffin balls increased from four to eight, the temperature of the paraffin balls decreased faster because of the increased total surface area for heat transfer. As the paraffin balls harden, the tank temperature distribution becomes more uniform. Furthermore, using more paraffin balls reduced the pressure drop across the tank, indicating an increased fluid flow and stability in the energy storage and release process. Based on these findings, it is suggested to utilise a TES tank with a larger number of paraffin balls (eight) to improve heat transfer rate and temperature uniformity in residential applications. This arrangement can improve the overall performance and reliability of PCM-based thermal energy storage systems. Future research may explore longer simulation times, different PCM materials, and additional design parameters to further improve the performance of these systems.

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