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Numerical study of thermal storage tank lagged with phase change materials for domestic hot water application

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Abstract

Phase change materials (PCMs) are gaining increasing attention and becoming popular in thermal energy storage because they can store thermal energy as latent heat through phase transitions. There are large numbers of PCMs that melts and solidifies at a wide range of temperatures, making them attractive in several applications including application for domestic use. The latent heat storage capability of PCMs when deployed in thermal energy storage technology improves the thermal storage efficiency. This study investigates the numerical modelling (using TRNSYS software) and thermal performance of a Phase Change Material (PCM)-lagged thermal storage tank (TST) for domestic hot water systems. A computational model was developed to simulate heat retention in PCM-lagged tanks using paraffin, PEG 4000, and sodium thiosulphate as storage media. Results indicate that PCM-lagged tanks significantly outperform conventional insulated tanks, maintaining water temperatures above 52.31°C after 24 hours compared to 24.65°C in non-PCM tanks. Sodium thiosulphate emerged as the most cost-effective PCM, offering optimal thermal stability at lower costs, while PEG 4000 demonstrated superior heat retention in larger volumes. Smaller tanks (0.01 m^3) heated rapidly but cooled faster, whereas larger tanks (0.10–0.13 m^3) exhibited prolonged heat retention, making them ideal for sustained demand.

Keywords: Latent Heat, Phase Change Materials, Sensible Heat, Thermal Energy Storage

Introduction

The need for energy is as old as man. Man uses energy for several utilities since from the olden days. The fast growing technological and economic development in our societies has also increased the demand for energy. The most consumption of energy comes from burning of fossil fuels. The side effect of burning fossil fuel to generate energy is environmental pollution and climate change. To effectively utilize energy and reduce the green house effects efforts are being shifted towards various sources of sustainable and renewable energy (Lin et al., 2018). In many parts of the world, direct solar radiation is one of the most prospective sources of renewable energy, however, its intermittency reduces the energy conversion efficiency and becomes the major setback (Waterson, 2017).

To address the intermittency problem, energy storage devices are developed, and they are as important as developing new sources of energy. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. (Garg HP et al,1985) It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. Energy storage is the capture of energy

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produced at one time for use at later time. It comes in multiple fumes including radiation, chemical, gravitational potential, electricity, elevated temperature, latent heat. Energy storage involves converts energy from forms that are difficult to conventional, economical storage forms (Thamaraikannn et al., 2017).

Thermal energy storage (TES) is a form of energy storage with promising solution to energy conservation and has undergone rapid development. The implementation of TES enhances the overall efficient and the dispatchability of power generation applications with renewable sources (Verdier et al., 2014). TES, which utilizes the change of the internal energy within the storage media, can be classified into thermochemical-, sensible-, or latent heat storage. Compared to sensible heat, latent heat storage is a more efficient method and provides a much higher energy density with a smaller temperature difference between storing and releasing heat (Sarbu & Sebarchievici, 2017).

Phase change materials (PCM) are ‘‘Latent’’ heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change in state, or ‘‘Phase.’’ Initially, these solid–liquid PCMs perform like conventional storage materials, their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, PCM absorbs and release heat at a nearly constant temperature (Fig 1) and store more heat per unit volume than sensible storage materials such as water, masonry, or rock. Many PCMs are known to melt with a heat of fusion in any required range. However, for their employment as latent heat storage materials these materials must exhibit certain desirable thermodynamic, kinetic, and chemical properties. Moreover, economic considerations and easy availability of these materials must be kept in mind.

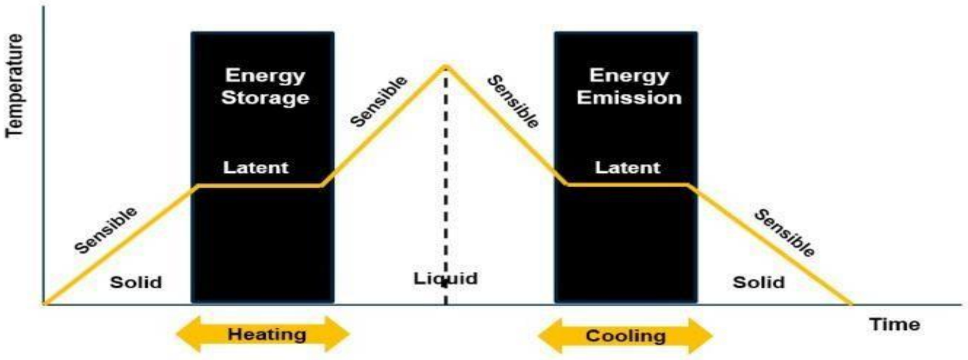

Fig. 1. Schematic diagram of the phase change transition of PCM (Du et al., 2018).

Currently, the application of PCM has been widely developed in different fields including, heating, and cooling of domestic buildings, solar power plants, solar drying systems, photovoltaic electricity generations, refrigerators, waste heat recovery and domestic hot water systems. This review attempts to summarize the recent developments in the field of thermal energy storage and of PCM as a means of thermal energy storage. Finally, the practical applications of PCM for domestic use were also reported.

Thermal Energy Storage (TES)

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat or thermochemical or combination of these. Sensible heat storage is due to temperature change of material while latent heat storage is due to the phase transformation either it is solid-liquid, liquid-gas or solid-solid. Different types of thermal energy storage are shown in figure-2 (Kumar & Shukla, 2015).

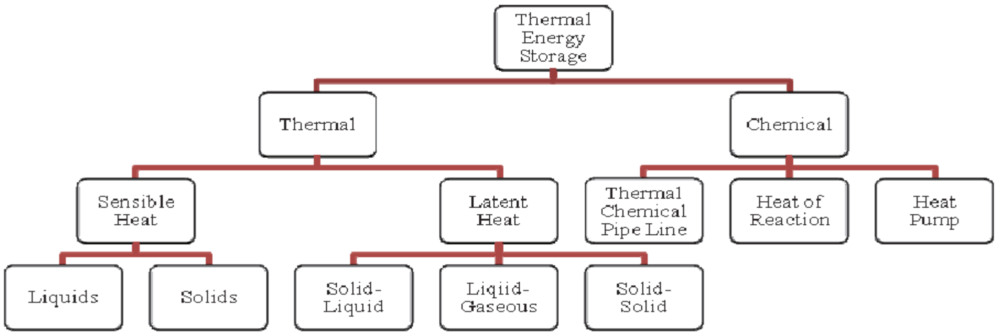

Fig. 2. Different types of thermal energy Storage

Sensible Heat Storage

Sensible heat storage (SHS) systems use energy stored or extracted by heating or cooling a liquid or a solid, which does not change its phase during this process, such as water, heat transfer oils and certain inorganic molten salts, and solid like rocks, pebbles, and refractory. In the case of solids, the material is invariably in porous form and heat is stored or extracted by the flow of a gas or a liquid through the pores or voids. Energy storage materials for the sensible heat storage won`t experience phase change process when they store thermal energy. The only process those materials will experience is the change of temperatures within one phase. Among all potential media for SHS, water has been the most promising candidate. Due to its high heat capacity (~4.2 kJ/kg · K) and low cost, it is often used in storage devices over the temperature range of 20-70°C. Also, as a liquid storage medium with high convective heat transfer, water allows the storage device to have higher heat injection and extraction rates compared to other solid heat storage media. Due to their simplicity and low cost, sensible heat TES devices have been used generally. However, SHS devices are not great candidates for long-term applications because of the following drawbacks.

a. Low energy storage density (~100 kJ/kg),
b. Heavy insulation required to minimize heat loss to the ambient,

c. Non-isothermal behavior during charging and releasing processes (Avghad et al., 2016).

Latent Heat Storage

Latent Heat Storage (LHS) is the transfer of heat as a result of a phase change that occurs in a specific narrow temperature range in the relevant material (Fallahi et al., 2017). LHS systems have certain benefits in comparison with SHS systems. The most important is the higher energy density per unit mass and per unit volume. This thermo-chemical system, rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the stored heat depends on the amount of storage material, the endothermic heat of reaction, and the extent of conversion. Latent heat storage can be done through solid-liquid, liquid-gas, solid-gas, and solid-solid phase transformations. Solid-gas and liquid-gas transition have a higher latent heat of fusion but their large volume changes on phase transition are associated with containment problems and rule out their potential utility in thermal storage systems. Large changes in volume make the system complex and impractical. The only two of practical interest are the solid-solid and solid-liquid (Sharma & Sagara, 2005).

Solid–Solid Transitions

This transition absorbs and release heat by reversible phase transitions between a (solid) crystalline or semi-crystalline phase, and another (solid) amorphous, semi-crystalline, or crystalline phase. It generally has smaller latent heat and volume changes than solid–liquid transition but offers the advantage of less rigorous container requirements and better design flexibility.

Solid-Liquid Transitions

This transition involves a change in the internal molecular arrangement from an ordered crystalline structure to a disordered amorphous one when temperature exceeds a critical threshold (i.e., the phase transition temperature). These phase changes are accompanied by a volume change, with volume typically increasing when the material becomes liquid. Some practical challenges of the solid liquid transitions are the need for containment or encapsulation when in liquid state to avoid leakage, the occurrence of phase segregation in mixed systems when going through multiple phase change cycles, material degradation, and hysteresis occurring between cooling and heating cycles. Despite these challenges, Solid-liquid transition has proved to be the most practical and economically attractive for use in thermal energy storage systems (Kumar & Shukla, 2015).

Phase Change Materials (PCMs)

Phase change materials (PCMs) are latent heat storage unit, they are made up of substances which have high heat of fusion that melt and solidify at a certain temperature, capable of storing and releasing large amount of energy. Heat is absorbed and released when materials changes phase from solid to liquid and vice versa.

The only phase change used in PCMs is solid-liquid phase. The others like liquid-gas phase transition have associated challenges already discussed under section 2.2 above. PCMs are classified into three types which are Organic, Inorganic and Eutectic as shown in Figure. 3

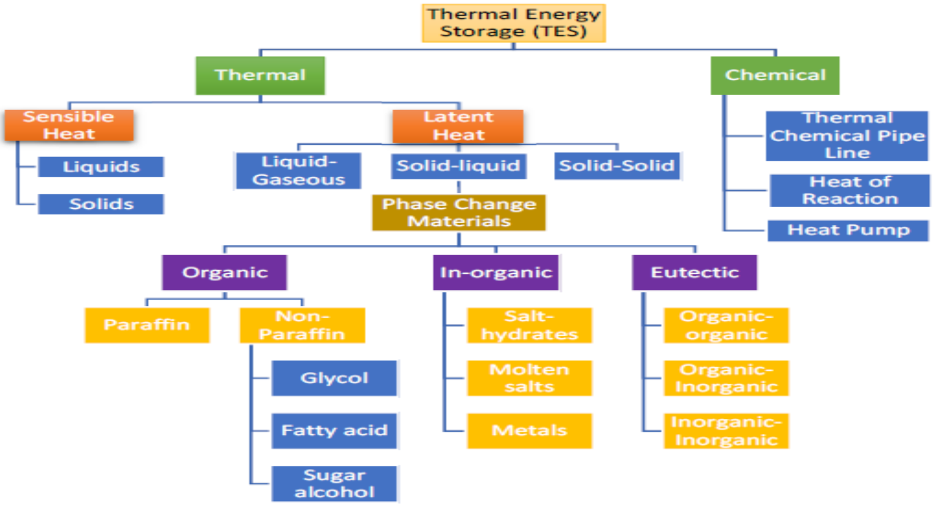

Figure 3. Thermal Energy Storage Showing Solid-Liquid Phase Change used in PCMs

Organic PCMs

There are two types of organic PCMs. The paraffin and the non-paraffin.

Paraffin Waxes

Paraffin waxes are naturally existing petroleum bi-products that have their unique phase-change temperature. These products are manufactured by major petrochemical companies so their availability could be limited. They can be toxic, flammable, and expensive. They have infinite life cycles, and the price varies with changes in petroleum prices globally. Paraffin comprises saturated hydrocarbons (alkanes of formula $C_nH_{2n}O_2$) having essentially the same characteristics as organic materials. The higher the carbon number, the higher the melting point of paraffin. Additionally, the carbon numbers also influence the thermal features (peaks for melting and crystallization temperature) of paraffin. Paraffin is generally stable below 500K, do not have a significant volume change when melting, and possess a low vapor pressure in melt condition. The main reason behind paraffin's qualification as an energy storage material is its accessibility in a wide range of temperatures. They are consistent, safe, knowable, and generally noncorrosive.

Non Paraffin Waxes

Non Paraffin Waxes there are three organic PCMs namely glycol fatty acids and sugar alcohols. Each are separately considered as follows.

Glycol

Glycol generally refers to any of the class of organic compounds in the alcohol family. Glycol molecules always have two hydroxyls (-OH) attached to two different Carbon atoms in the molecular chain. Glycol is often used to refer to the smallest member of the class-ethylene glycol also called 1,2-ethanediol, with molecular formula $HOCH_2CH_2OH$ (ethylene molecular formular been CH_2CH_2). Ethylene glycol has excellent heat transfer properties and is used as a coolant for internal combustion engines. The main task of the coolant is to effectively collect heat energy from the engine and dissipate it through the radiator to the environment. The coolant, therefore, prevents the engine from freezing in winter and, at the same time, acts as a coolant at high temperatures in summer.

The low viscosity of glycols contributes to their excellent heat transfer efficiency however ethylene glycol is very toxic should never be used where contacts with humans or animals are possible. Propylene Glycol is not toxic and can be used where contacts with humans are likely. It has higher specific heat and viscosity it is however less efficient than ethylene glycol at lower temperature.

Fatty Acids

Fatty Acids are naturally existing and are obtainable from renewable or reused raw materials like animal fat and vegetation such as beef tallow, lard, palm oil, coconut, and soybean (bio based PCMs). They have a general chemical formula $CH_3(CH_2)_{2n}COOH$. Advantages of fatty acids include congruent melting and cooling, high latent heat of fusion, low cost, fire resistance, nontoxicity, very little sub cooling and volume change, good chemical, and thermal stability after many thermal cycles, and rapid degradation when disposed of, reducing end-of-life environmental impact.

Fatty Acids major drawback is in their limited thermal conductivity, which reduces heat storage and release rates during phase transitions, due to their acidic nature, fatty acids are more aggressive than paraffin toward the surrounding environment and can also be flammable at high temperatures. Examples of fatty acid are formic acid, acetic acid, stearic acid, glycolic acid, alpha naphthol, quinone and benzoic acid. The phase change temperature and latent heat of fatty acids are increasing with the increase of the carbon chain length (Yuan et al., 2014).

Sugar Alcohol

Sugar Alcohol are organic compounds derived from sugars and containing one hydroxyl group (–OH) attached to each carbon atom. The sugar alcohols differ in the length of their chains. Most have 5 or 6-carbon chains. This is because they are derivative of pentoses (five-carbon sugars) and hexoses (six-carbon sugars). Each carbon in the chain has one –OH group attached to it. They are white, water-soluble solids that can occur naturally or be produced industrially by hydrogenating sugars. The use of Sugar alcohols as PCMs is very promising due to their high storage capacity, safety, and economic attributes. Their phase change temperatures make them fit for medium temperature storage. To guarantee a long PCM working lifetime sugar alcohol should be tested under a repeated cycles of freezing/ melting to ascertain the constancy of the thermophysical properties (Solé et al., 2014).

Inorganic PCMs

Inorganic PCMs are salt hydrates, nitrates, and metallic having a rather high heat of fusion. These materials also present high latent heat values; they are non-flammable, cheap, and readily available. Some of these disadvantages are their corrosiveness to most metals, instability leading to phase decomposition, and improper re-solidification. Sub-cooling is another serious problem associated with all hydrated salts

Salt Hydrates

Salt hydrates can be considered alloys of inorganic salts (AB) and water (H_2O), resulting in a typical crystalline solid of general formula ($AB \cdot xH_2O$) (Sharma & Sagara, 2005). Their phase change transition can be regarded as a dehydration or hydration of the salt, although this process can be assimilated to a melting or a freezing of the compound. Salt hydrates usually melt to either a salt hydrate with fewer moles of water, or to its anhydrous form. During the phase change transition, liquid water released from the hydrated salt dissolves the formed non-hydrated salt molecules.

Nitrates

Nitrate is a polyatomic ion with the chemical formula NO^{-}_3. Salts containing this ion are called nitrates. In inorganic nitrate salts, the most used anions are nitrates, nitrate/nitrite mixtures, carbonates, chlorides, and fluorides, and cations belonging to alkaline elements such as sodium or potassium (Pfleger et al., 2015). In this sense, materials such as potassium nitrate (KNO_3), sodium nitrate ($NaNO_3$), and sodium nitrite ($NaNO_2$) have melting points at suitable temperatures to be used in thermal storage applications, exceeding 150 °C, such as solar thermal systems .

Metallic

The major drawbacks in use of salts for higher temperature applications are low heat conductivity, corrosivity, the big change in volume on melting, considerable overcooling, and high cost. Metals, as a rule, are devoid of these lacking. Metals offer higher heat transfer rates compared to salts. TES systems where the rates of heat transfer should be considered over the net energy storage alone, replacing salts with metallic PCMs will have a considerable impact. One of the pioneering works on this was the investigation of the suitability of binary and ternary alloys of Al, Cu, Mg, Si, and Zn covering a temperature range from 343°C to 946°C (Birchenall & Riechman, 1980). It was reported that the best heat storage densities on a mass or volume basis are obtained with alloys rich in Si or Al.

Eutectic PCMs

Eutectic is a congruent composition of two or more components in which each of it melts and freezes as a single compound. The eutectic PCM can be a mixture of two or more compound, which can be either organic materials, inorganic materials, or both. The mixture of these compound forms a crystal during crystallization. They melt and freeze to an intimate mixture of crystals simultaneously without separation. The main issue with eutectic PCMs is that they are costly, as they are two or more times costlier than the organic or inorganic PCMs. They however have a wide range of phase change temperature, exhibit good chemical and thermal stability, have high heating capacity, and shows little or no super-cooling. There are three types of eutectic PCMs, which are organic-organic eutectic PCMs (EO-PCM), inorganic-inorganic eutectic PCMs (EI-PCM) and organic-inorganic eutectic PCMs (EOI-PCM)

Eutectic Organic PCM

Eutectic Organic PCM is a mixture of two or more organic PCMs which function as a single candidate and changes the phase coherently. The greatest advantage of EO-PCMs is their customized properties. They can be prepared in such a way that they demonstrate the desired properties (Singh et al., 2021). Many a times, eutectic mixtures of fatty acids show lower melting point than individual PCMs but possess excellent properties like individual organic PCM, hence for TES applications, the EO-PCM can be chosen as novel PCMs. The other advantages of EO-PCM are their capability to achieve more desirable properties like specific operating phase change temperature or high latent heat thermal energy storage capacity for each unit of volume.(Yang et al., 2020)

Eutectic Inorganic PCM

Eutectic molten salts are two or more molten salts mixed, and that have the characteristic of congruent melting and solidification without material's separation (Huang X et all). Eutectic molten salts are new materials composed of two or more molten salts, with a single melting point and latent heat. There are different types of eutectic inorganic PCMs possible, mixtures to hydrates, nitrides and metallic alloys depending on the desired characteristics of the new materials. The general advantages of EI-PCM are high melting temperature, wide phase change temperature range, relatively large thermal energy storage capacity and relatively stable thermal properties. The thermal conductivity of molten salts is higher compared with that of Eutectic organic PCMs (Ran et al., 2021)

Eutectic Organic-Inorganic PCM

There are rare studies to date on inorganic-organic eutectic systems. This is because of the incompatibility between most organic and inorganic materials. A critical part of latent heat energy storage technology is that the thermal characteristics of phase change materials are directly related to energy efficiency. The ideal phase change materials need to meet the requirements of thermal, dynamic, chemical, and economic characteristics. To meet these desired characteristics attempts through research are being made to produce eutectic mixtures from inorganic and organic materials despite their seeming incompatibility.

In an experiment undertaken, a prepared mixture of Aluminum sulfate hydrated salts and inorganic PCM (aluminum potassium sulfate dodecahydrate (Alum) and aluminum ammonium sulfate dodecahydrate (AAS)) each with organic Erythritol ($C_4H_{10}O_4$) to make them adaptable to temperature requirements of various fields, the melting temperature needs to be manipulated without compromising its latent heat. The results shows that the melting temperatures of the two were 72.46 °C and 73.20 °C when containing 35 weight percentage and 37 weight percentage of erythritol, respectively. It was worth noting that they still possessed high latent heat of 243.4 J/g and 257.4 J/g (Wenjuan et al., 2022)

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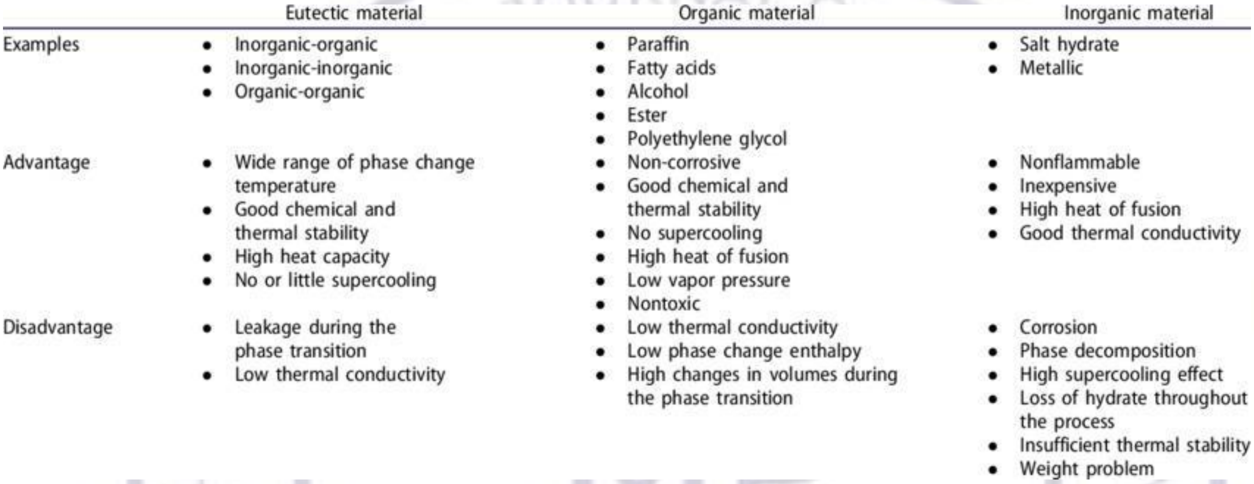
1. **Table 1. Advantages and disadvantages of organic, inorganic, and eutectic PCM**



	Eutectic material	Organic material	Inorganic material
Examples	Inorganic-organic Inorganic-inorganic Organic-organic	Paraffin Fatty acids Alcohol Ester Polyethylene glycol	Salt hydrate Metallic
Advantage	Wide range of phase change temperature Good chemical and thermal stability High heat capacity No or little supercooling	Non-corrosive Good chemical and thermal stability No supercooling High heat of fusion Low vapor pressure Nontoxic	Nonflammable Inexpensive High heat of fusion Good thermal conductivity
Disadvantage	Leakage during the phase transition Low thermal conductivity	Low thermal conductivity Low phase change enthalpy High changes in volumes during the phase transition	Corrosion Phase decomposition High supercooling effect Loss of hydrate throughout the process Insufficient thermal stability Weight problem

PCMs storage methods.

There are several methods of storing PCMs while in service to reduce its reactivity with the external environment and to decrease its evaporation and diffusion rate. These storage methods also make the processing procedures less energy demanding. They are as follows.

Encapsulation

Encapsulation through the encapsulation technology PCMs with a larger heat transfer area are produced and their reactivity with the external environment is greatly reduces. Their volume change is equally controlled during phase change. Due to these stated reasons (Delgado et al., 2012), microencapsulated phase change materials (MEPCM) have attracted considerable attention for a long time.

The presentation of the working principle of encapsulated PCM in Fig 4. Shows the center part as a PCM, and the shell or capsule part represents the encapsulation material (Nazir et al., 2019). After heating, the PCM will melt while the shell remains solid, as shown in Fig. 4a. The PCM undergoes a latent heat change at constant temperature, while also storing a certain amount of thermal energy, as shown in Fig. 4b. When cooled below the melting point, the PCM returns to its original solid state by releasing the absorbed heat (Fig.

4a). The main parameters of the encapsulation are the thickness of the coating material, the encapsulation size, the thickness of the shell, and the geometry of the encapsulation (Hu & Yu, 2014).

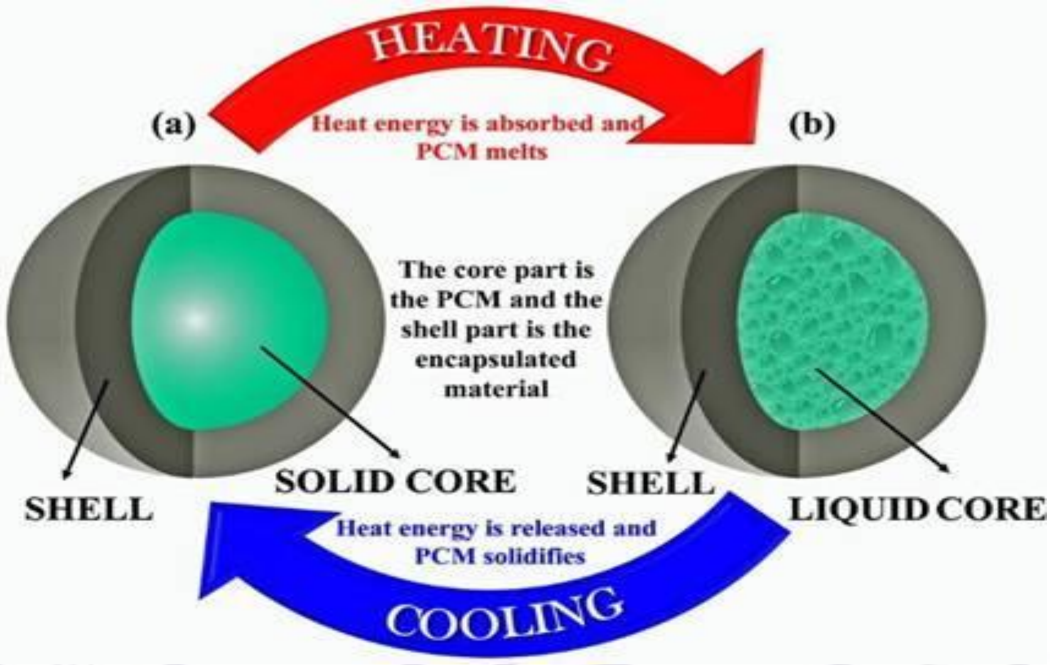


Figure 4: Working principle of the encapsulated PCMs.

Shape Stabilized PCMs

The micro-encapsulation of PCMs has some problems that needs to be solved. They include leakage of the melted PCM when a capsule shell is damaged, heat resistance of the capsule shell and extra cost incurred to encapsulate the PCM. To prevent the leakage a new type of wrapped PCM was introduced called “shape stable PCM” (SSPCM). It is produced by embedding a PCM into a frame material structure that is porous or that has a 3D network also known as a form-stable phase change material (FSPCM).

This “frame materials” are called support materials and they can restrict the flow of PCM to prevent leakage. Recently they have attracted a lot of interest due to their excellent shape retention capacity even after a high number of thermal cycles without any encapsulation (Zhou & He, 2015). The SSPCM has several remarkable features which include large heat capacity in the phase transition temperature region, suitable thermal conductivity, maintaining shape stability, and preventing leakage during the entire phase transition process.

Foam Formation

PCMs can also be stored by incorporating them into Polyurethane (PU) foams. Polyurethane (PU) foams have wide application for thermal insulation as the ultimate energy savers. They have high mechanical and chemical stability at both high and low temperatures, they are recyclable and do not contain chlorofluorocarbons. There are three methods of incorporating PCM into the polyurethane foam structure. They are:

(i) injecting and dispersing PCM directly into PU foam

(ii) trapping PCM in the composite structure during the synthesis of PU foam

(iii) chemical grafting or preventing copolymerization of PCM (such as Polyethylene Glycol-PEG).

Test conducted on the direct incorporation of PEG600, PEG1000, and PEG1500 and their mixtures into PU foams, which are commercially used as insulating materials. The results show that PU foams with different PEG components and contents exhibit different thermal properties and are suitable for different application scenarios, such as temperature regulation in mild and hot environments to prevent discontinuity when the external temperature suddenly rises or falls (Sarier & Onder, 2008).

PCM selection, domestic applications and used methodology

Some domestic applications of PCMs are given in Table 2 below

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Table 2. Domestic applications of PCMs used methodology and results

PCM Material	**Methodology**	**Results**	**Domestic Application & References**
1. Magnesium Chloride ($MgCl_2$) 2. Magnesium Chloride $MgCl_2$ + Average material as graphite foam 3. Magnesium Chloride + anisotropic thermal conductivity and temperature-dependent material properties for graphite foam	Three-dimensional 610 °C heat transfer simulations were conducted for each of the 3 PCM materials (as storage system) using commercial software COMSOL.	1. Graphite foam generally helps to significantly improve the heat transfer performance 2. The energy efficiency of Material with graphite foam was also improved. 3. The number of heat transfer fluid pipes required in the storage tank containing material 3 reduced by a factor of eight.	Concentrated Solar Plant (CSP) for generating energy in the home (Zhao et al., 2014).

1. Solar Water heater with Sodium carbonate decahydrate Na2CO3 10H2O as Phase Change Material (PCM) 2. Solar Water Heater without any PCM	The performance of a solar collector system (with PCM- Na2CO3 10H2O and without PCM) was experimentally investigated for efficiency.	The solar collector system with PCM is more effective than convectional systems	Solar water heating system (Varol et al., 2010)
1. CaCl2·6H2O (Calcium chloride hexahydrate) as PCM with insulation materials in Tank. 2. Insulation material only without any PCM.	Two Tanks with latent heat storage in combination with hot water collector was designed and tests were held under Elazig, Turkey climatic conditions between July and November for the tank with PCM and for the tank without PCM.	The highest thermal efficiency value in the study was obtained as 58% in July around hour 13:30 from the tank in which phase change material (PCM) was used.	Solar water heating system (Kılıçkap et al., 2017).
1. An expanded perlite (EP) is composited with a salt hydrate mixture of CaCl2·6H2O and SrCl2·6H2O to form a PCM brick 2. A foam insulation brick without the composited hydrate PCM mixture	Both materials are applied as the roof of a dual test room and the temperature of the room is taken for the same period.	1. The PCM brick decreased the indoor peak temperature whereas the foam insulation brick did not. 2. The hysteresis in the indoor temperature rises for the PCM brick, compared with the foam insulation brick. **Temperature hysteresis happens where a temperature's rise or fall trails behind the act of supplying or cutting off the heating/cooling supply.*	Building energy conservation (Fu et al., 2017).

1. Paraffin wax is used as PCM in spherical capsules as storage material in the tank of solar water heater. 2. Solar water heater without any PCM as storage material	The effect of three solar radiation intensity, i.e. weak, mean and strong are studied on the solar water heater with paraffin wax PCM as a storage material and without any storage material. The time length the solar water heater can supply hot water have been compared with PCM and without PCM.	1. It is observed that by using PCM in the tank the energy storage density is increased in the tank up to 39% 2. Also, it is observed that solar water heaterwith PCM, can supply hot water with specified temperature at 25% longer time.	(Fazilati and Alemrajabi, 2013)

Source: Author’s Compilation, 2023

Materials

The current state of research on the use of phase change material for lagging is generally very minimal and reveals a notable gap in the numerical study of paraffin, poly ethylene glycol (PEG 4000) and Sodium thiosulphate to lag a thermal storage tank. This numerical study seeks to contribute valuable insights that can potentially advance the use of phase change material to improve the efficiency and heat retention capacity of thermal storage tank. The PCM energy storage tank in this study is a cylinder tank consisting of the water tank and PCM tank integrated as a single tank as seen in Fig. 1(a). The water and the PCM in the tank are at the same height and divided into n layers called nodes of equal size for modelling purposes. The conventional tank as seen in Fig 1(b) is of equal dimensions to the PCM tank for the purpose of fair comparison. TRNSYS 18 Software was used for the numerical study of the thermal storage tank lagged with PCMs. The PCM materials used for the lagging in this study is Paraffin, Poly ethylene glycol 4000 and Sodium thiosulphate

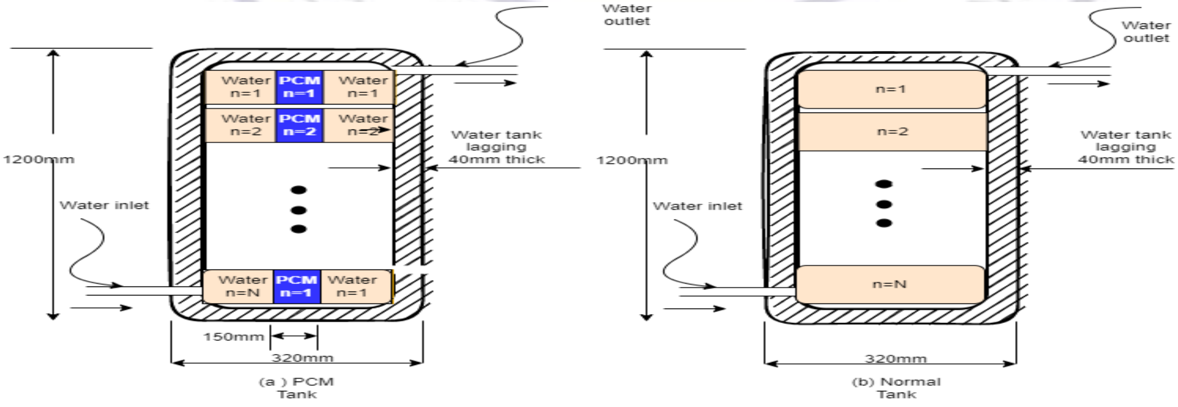

Figure 5: Cross section of the PCM and normal hot water tank

Method

Figure 6 below shows the methodology used for the system modeling and analysis.

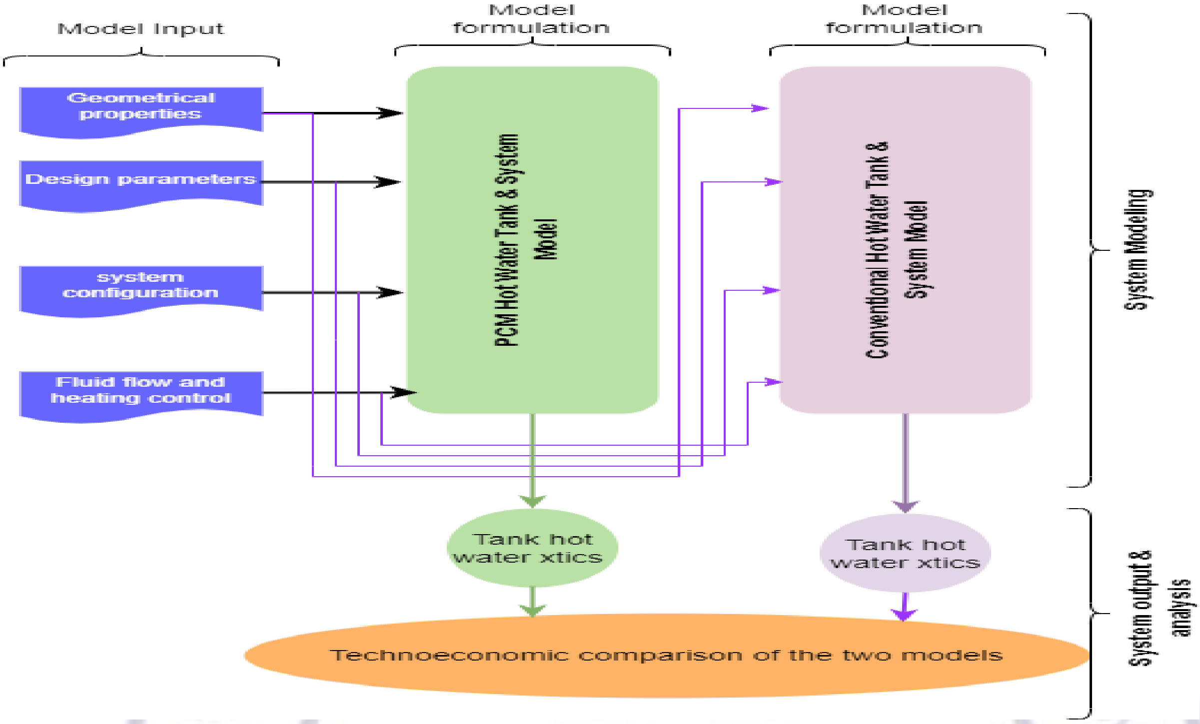

Figure 6: System modeling and analysis

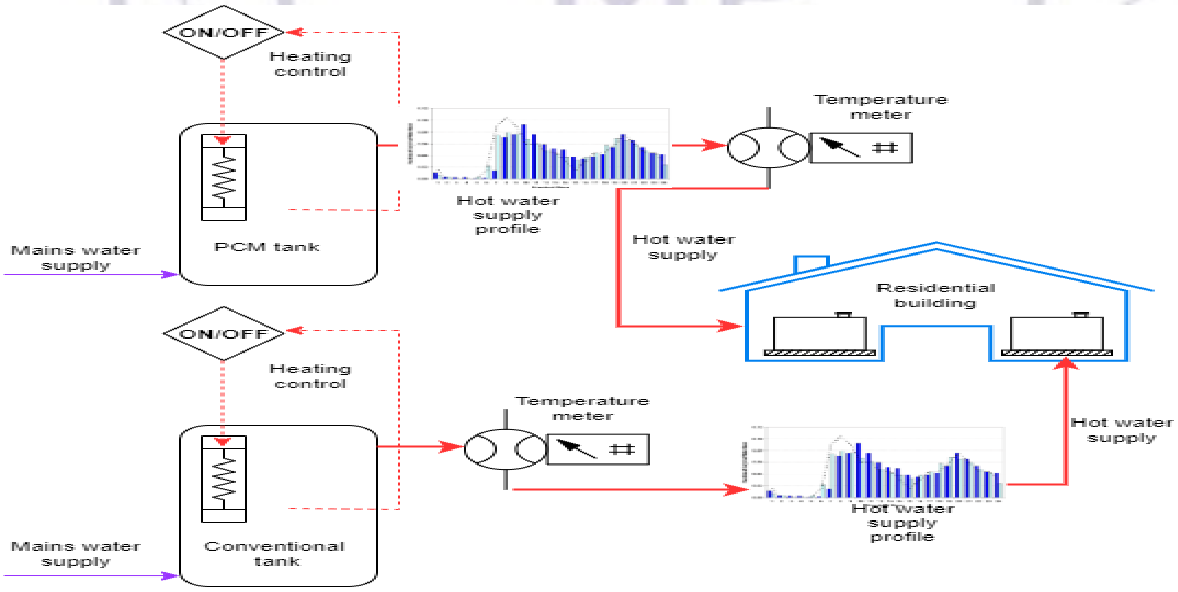

Figure 7: Flow diagram for the model formulation of the PCM hot water heating system

Mathematical modeling of Hot Water Tanks

In this study, a uniform steady flow distribution in the flow direction inside the energy storage is assumed. Therefore, only energy balance equations are considered. The energy models are calculated by the finite difference method in the implicit formulation. The PCM hot water tank model does not exist in the TRNSYS

18 simulation library and therefore needs to be developed based on theoretical equation that describes the thermal behavior of the PCM tank as found in different studies (Weiqiang Kong et al. 2022).

Heat Stored

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_{ap}(T_f - T_i) \qquad \ldots (1)$$

Latent Heat Stored

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta H_m + \int_{T_m}^{T_f} mC_p dT \qquad ..(2)$$

The energy differential equation in one dimension for the cylindrical water tank

$$\frac{\partial \rho c T_W}{\partial t} + \frac{\partial \rho c u T_W}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial T_W}{\partial x}\right) + h_{hl} A_s (T_a - T_w)/\, V + \Gamma A_{pw}\left(T_p - T_w\right)/V \qquad \ldots (3)$$

By finite difference method equation 3 becomes

$$mc\frac{T_i - T_i^0}{\Delta t} = kA_c \frac{T_{i-1} - T_i}{\Delta x} + kA_C \frac{T_{i+1} - T_i}{\Delta x} + mc(\overset{\cdot}{T}_{\imath-1} - T_\imath) + h_{hl} A_s (T_a - T_i) + \Gamma A_{pw}\left(T_{pi} - T_i\right) \quad \ldots (4)$$

Sorting out the term in Eq. 4, it is further written as shown in Eq. 5

$$\left(-\frac{kA_c}{\Delta x} - \dot{m}c\right) T_{i-1} + \left(\frac{mc}{\Delta t} + \frac{2kA_c}{\Delta x} + h_{hl} A_s + \dot{m}c + \Gamma A_{pw}\right) T_i + \left(-\frac{kA_c}{\Delta x}\right) T_{i+1} = h_{hl} A_s T_a + \Gamma A_{pw} T_{pi} + \frac{mc}{\Delta t} T_i^0 \qquad \ldots (5)$$

The boundary conditions for the nodes can be found using Eq. 6 and 7 below

$$\left(-\frac{kA_c}{\Delta x}\right) T_1 + \left(\frac{mc}{\Delta t} + \frac{2kA_c}{\Delta x} + h_{hl} A_s + \dot{m}c + \Gamma A_{pw}\right) T_1 + \left(-\frac{kA_c}{\Delta x}\right) T_2 = h_{hl} A_s T_a + \Gamma A_{pw} T_{p1} + \frac{mc}{\Delta t} T_1^0 \qquad \ldots (6)$$

$$\left(-\frac{kA_c}{\Delta x}\right) T_{N-1} + \left(\frac{mc}{\Delta t} + \frac{2kA_c}{\Delta x} + h_{hl} A_s + \dot{m}c + \Gamma A_{pw}\right) T_N + \left(-\frac{kA_c}{\Delta x}\right) T_N = h_{hl} A_s T_a + \Gamma A_{pw} T_{pN} + \frac{mc}{\Delta t} T_N^0 \qquad \ldots (7)$$

Similarly, conducting an energy balance on the PCM region of the tank Eq. 8 is applicable

$$\frac{\partial \rho H_p}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T_P}{\partial x}\right) + \Gamma A_{pw}\left(T_w - T_p\right)/\, V \qquad \ldots (8)$$

The dynamic energy change of Eq. 8 is described by the enthalpy of PCM since its nonlinear energy-temperature relationship. This phenomenon is described and estimated from the Eq. 9 (Weiqiang et al. 2022).

$$\mathrm{H_p} = \begin{cases} \mathrm{c_s T} & \mathrm{T < T_{m1}} \\ \mathrm{c_s T_{m1}} + \frac{\mathrm{E_L(T - T_{m1})}}{\mathrm{T_{m2} - T_{m1}}} & \mathrm{T_{m1} \le T \le T_{m2}} \\ \mathrm{c_s T_{m1} + E_L + c_i(T - T_{m2})} & \mathrm{T > T_{m2}} \end{cases} \qquad \ldots (9)$$

The hot water thermal hourly energy requirement will be estimated based on the volume of hot water tank using Eq. 10

$$\mathrm{\dot{Q}_{DHWL}} = \mathrm{\dot{m}_L C_p (T_L - T_{mains})} \qquad \ldots (10)$$

The quantity of thermal energy delivered by the proposed system to meet building's hot water demand is estimated as shown in Eq. 11

$$\dot{Q}_d = \dot{m}_L C_p (T_d - T_{mains}) \quad \ldots(11)$$

The Since the extra energy to heat water to the desired hot water temperature is only required when the water temperature in the heater tank falls below the designed temperature, the required auxiliary thermal energy is calculated as expressed in Eq. 12

$$\dot{Q}_{aux} = \max\left(\left(\dot{Q}_{DHW} - \dot{Q}_d\right), 0\right) \quad \ldots(12)$$

Economic performance evaluation of the proposed system

The present worth (PV) of an investment from the future worth (F_n) is calculated from Eq. 13 and Eq. 14 (Roy et al. 2021).

$$PV = PVIF_n \times F_n \quad \ldots(13)$$

$$PVIF_n = \frac{1}{(1+d)^n} \quad \ldots(14)$$

Where

PV = present value of cash flow,
$PVIF_n$ = present value interest factor,
d = the annual discount rate,
n = the base year of analysis after year zero
F_n = the assumed or expected cash flow in n years in the future.

This study assumes that the energy project is operational with no increase in load for 25 years

Assuming that the annual saving of the system is E_s and the power degradation factor is δ then the value of the Life Cycle Savings (LCS) evaluated in any base year n is found from Eq.15

$$LCS = E_s(1-\delta)^n(1+i)^n \, PVIF_n$$

Results and Discussions

i. Data obtained from thermal storage tank lagged with Paraffin, PEG 4000 and Sodium thiosulphate shows that these tanks exhibited thermal storage efficiency and energy savings capability. Tanks lagged were found to retain heat above (after 24 hours) 52.31°C as against 24.65°C recorded for the ordinary tank without any lagging, thereby reducing the time and cost of energy needed to re-heat the water

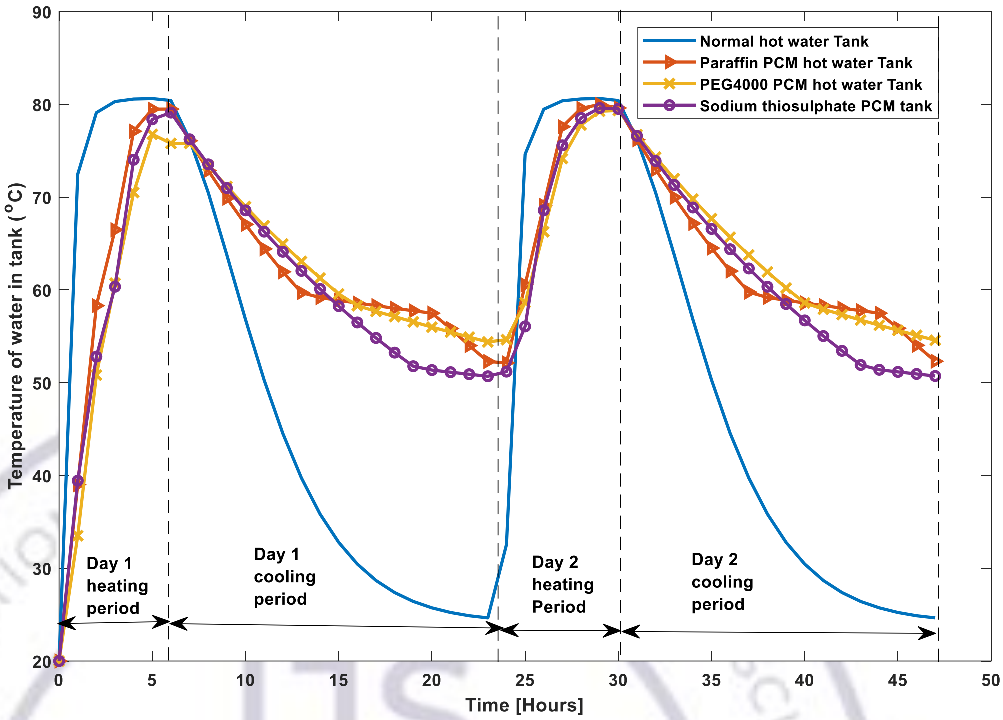

Figure 8: Thermal characteristics of Non PCM and PCM tanks

ii. Performances of the PCMs varies with the size of the tanks, small volumes (0.01 m³) tanks show rapid heating reaching peak temperatures quickly but cooling down rapidly, while large volumes (0.10 m³ and 0.13 m³) show slower to heat but excellent at maintaining temperature, reducing heat loss over time.

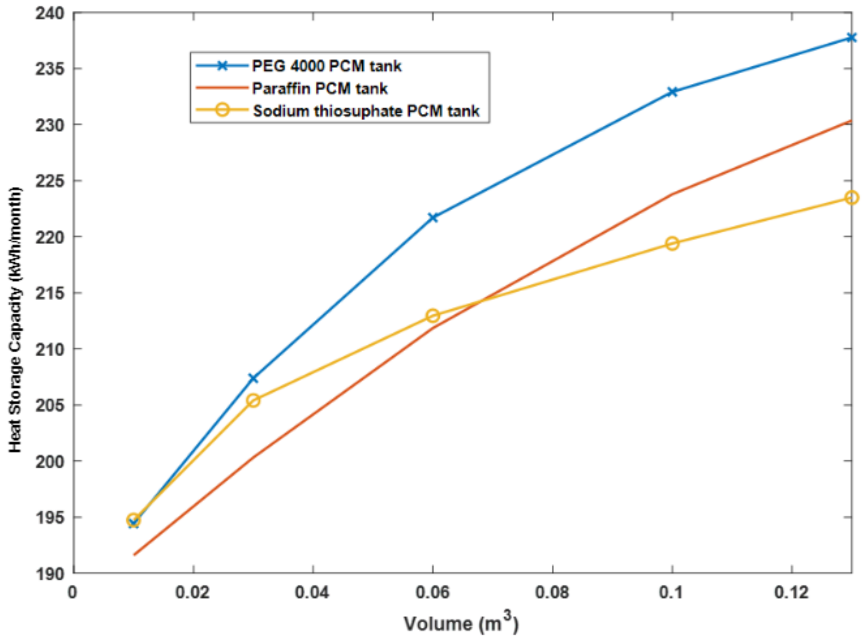

Figure 9: Variation of the heat storage capacity of the different PCM tank based on different volume of the PCM material used for lagging

iii. The quantity and cost of the PCM material needed to lag the tank also shows that Sodium Thiosulphate PCM consistently offers the lowest cost per kWh across all volumes, making it the most economical choice for energy storage. It is the most cost-effective option compared to Paraffin and PEG 4000 PCM. Sodium thiosulphate PCM, particularly in larger volumes, also offers strong performance in maintaining temperatures over time, making it ideal for applications that require sustained thermal energy.

Table 2 Cost of PCM material estimated based on their mass at different volumes

	PEG 4000 PCM @ 1.86USD/kg		Paraffin PCM @ 0.98USD/kg		Sodium thiosulphate PCM @ 0.34USD/kg	
Volume of PCM material	Mass (kg)	total cost	Mass (kg)	total cost	Mass (kg)	total cost
0.01	12	33480	9.2	13524	16.6	8466
0.03	36	100440	27.6	40572	49.8	25398
0.06	72	200880	55.2	81144	99.6	50796
0.10	120	334800	92.0	135240	166	84660
0.13	156	435240	119.6	175812	215.8	110058

Conclusions

i. The study successfully developed a detailed numerical model that simulated the operation of thermal storage tank (TST) for hot water tanks. This model serves as a tool for predicting the system behavior under varying conditions

ii. The performance evaluation of the TSTs lagged with phase change material revealed its thermal storage efficiency and energy savings capability. The system achieved extended thermal stability and reduced heat loss, leading to potential energy savings and more consistent hot water availability. Thus, for applications requiring sustained temperature maintenance and reduced energy consumption, PCM tanks are a more efficient choice

iii. The different factors affecting the thermal storage potential of the phase change materials were determined with the simulation techniques. By analyzing these factors, insights were gained into the PCMs performances. PEG 4000 offers the highest heat retention capacity at larger volumes, making it the most desired for systems requiring substantial thermal storage. Paraffin and sodium thiosulphate also provide valuable alternatives, with sodium thiosulphate being particularly effective at smaller volumes.

iv. The smaller volumes start providing returns earlier due to lower initial costs, making them more financially attractive in the short term. Larger volumes take longer to reach a break-even point but eventually yield higher NPV. Smaller volume of PCM tank is suitable for projects with budget constraints or shorter investment horizons. While larger volume PCM tank is suitable for projects where long-term performance and energy savings are prioritized.

Recommendations

i. That TST lagged with PCMs systems ensures that there is Hot water supply stability, as the temperature of the stored water remains relatively constant for longer periods compared to conventional storage tanks. Thus, providing hot water during fluctuating domestic hot water demands without needing to wait for reheating or incurring additional energy costs.

ii. That the Integration with renewable energy systems such as solar thermal systems, as such integration will reduce the dependency on traditional heating systems and minimizes reliance on non-renewable energy sources, making the system more sustainable.

iii. That TST lagged with PCMs systems are adaptable and can be scaled up or down depending on the size of the household or the specific needs of a building. Smaller systems can be used in individual homes, while larger systems can be employed in commercial or industrial applications.

iv. This study also recommends that budget-constrained projects should prioritize smaller-volume PCM tanks to minimize initial capital costs and achieve faster returns on investment for a small-scale industrial process, or residential systems. While for a long-term sustainability-focused projects, adoption of a larger-volume PCM tanks to maximize net present value (NPV) over extended periods.

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