Chapter 3
Thermal Energy Storage Methods and Materials

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Abbreviations and Nomenclature

CTESM	Composite thermal energy storage materials
HTF	Heat transfer fluids
LTES	Latent heat energy storage
PCM	Phase change material
STES	Sensible heat storage
TCS	Thermochemical storage
TES	Thermal energy storage
TESM	Thermal energy storage material
VAR	Vapor absorption refrigeration
K	Thermal conductivity
TSD	Thermal storage density
CNTs	Carbon nanotubes
EG	Expanded graphite
GA	Graphene aerogel
GNFs	Graphite nanofibers
GnPs	Graphene nanoplatelets
GNPs	Graphite nanoparticles
$LiNaCO_3$	Lithium carbonates and Sodium carbonates
L-MWCNTs	Long Multi-walled carbon nanotubes
NG	Nano-graphite
OA	Octadecanoic acid
PA	Palmitic Acid

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3.1 Thermal Energy Storage Methods

3.1.1 Introduction

Thermal energy storage (TES) is an extensive technology adopted for energy conservation and reutilization due to its excellent practical importance. This technology is most suitable for especially for heating cooling applications. This can be used for wide range of applications, such as ice storage, heat storage, building, and agriproduct preservation applications. The TES technology showing a great impact on modern technology due to its wide range of adaptability. In this field, a significantly strengthening actions are required in domestic and commercial sectors to utilize the stored thermal energy up to its maximum potential. TES can considerably reduce or completely minimize the gap between the supply and energy demand. TES can also reduce non-renewable energy dependence from the society by fulfilling their energy requirements, alongside it is environment friendly. TES is a prominent part of thermal systems and desirable thermal systems should possess minimum energy loss with time so that stored thermal energy can be retained for longer-term use (Sharma et al. 2009). There are different modes of thermal energy storage which are shown in Fig. 3.1 with some examples and applications.

For each storage, mode offers different possibilities depending on the available temperature range and required application. TES through sensible heat storage mode is generally preferred for short-term storage because as the storage material has some surface temperature and tends to lose heat to the surrounding. One of the examples of liquid medium sensible heat storage is domestic solar water heater and example of solid medium sensible heat storage is spreading of pebbles in swimming pools, which will absorb heat during day time and slowly releases the heat when water temperature starts decreasing. Sensible heat storage capacity is relatively lower than the latent heat storage mode.

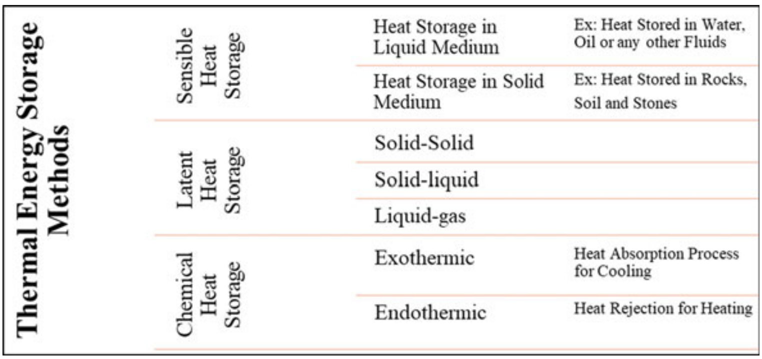

Fig. 3.1 Different modes of thermal energy storage with some examples (Chavan et al. 2018a)

Latent heat storage mode is preferably used due to its large storage capacity even at lower temperature ranges. As in latent heat, storage takes place through phase change process and storage material surface temperature is almost constant the heat loss is assumed to be very low. Most common example of latent heat storage is the conversion of water to ice.

Chemical heat storage mode is not widely used due to its limited energy storage capacity (limited heat absorption and heat rejection). It is preferred only for some specific applications, when the heat is to be removed from surrounding space an endothermic chemical reaction is triggered at specific temperature so the endothermic chemical reaction absorbs the heat and reduces the surrounding temperature. Similarly, when the heat supply is required exothermic reaction is triggered at specific temperature to release the heat from the chemical reaction (Muthukumar 2005).

3.1.2 Available Thermal Energy and Its Utilization

Most of the industries involve thermal processes within it, and small part of this thermal energy is either reused for secondary applications or it is simply left to the sink. Several industries with heat treatment processes of different stages can utilize it up to certain level but still, it is not been utilized up to maximum extent. For example, a textile industry uses hot water to separate the threads and process it for interweaving these individual threads, at later stage, these interweaved threads are sent to the dyeing where color pigment is slightly heated. In this complete process, the priorly heated water can be used for secondary heating application in the dyeing section. Another industry makes use of heat to convert it into gases, liquids, solids, evaporation of vapors, and generate heat from chemical reactions. Among others, scientists, engineers, technologists, researchers, and others must understand the heat transfer phenomenon and its practical application.

Solar energy is the largest source of thermal energy available the daytime available solar thermal energy can be stored and same can be utilized for night use. For example, a vapor absorption refrigerator (VAR) can be operated after sunset with stored solar thermal energy. Solar thermal energy storage can reduce the non-renewable energy dependency, especially in the rural places where availability of electricity is uncertain. A large-scale solar thermal energy storage-based VAR can be built for a particular public area so that they can store their agriproducts commonly without depending on the electricity with low cost. Figure 3.2 shows thermal energy utilization for different applications.

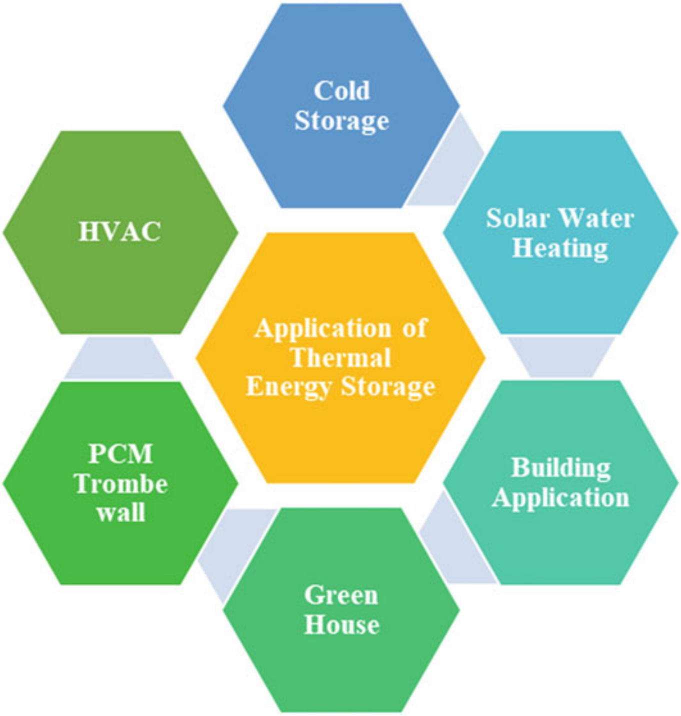

Fig. 3.2 Thermal energy utilization for various applications

3.1.3 Thermal Energy Storage

TES technology is recently most trending domain with its significant impact on modern technology. TES is more essential, especially during the energy intermittency like solar thermal energy. In winter, when solar energy is much less accessible and therefore less useful, the TES application is more important. It is important for society to create energy sources that are more environmentally friendly, as well as more efficient, which can then be used for heating and cooling buildings, providing power for aerospace, and for utility services as well. Most people favor TES technology for its superior characteristics such as lower energy costs, reduced energy consumption, enhanced indoor air quality, reduced initial and maintenance costs, and enhanced flexibility. Along with these TES exhibits some more advantages like condensed equipment size, supplementary efficient and active utilization of equipment, preservation of fossil fuels, and reduction of pollutant emissions (Mohamed et al. 2017). TES frameworks have a gigantic potential to build the viability of energy-conversion equipment use and for encouraging enormous scope in fuel replacements on the world's economy. TES is unpredictable and can't be assessed as expected without a nitty gritty comprehension of energy supplies and end-use contemplations.

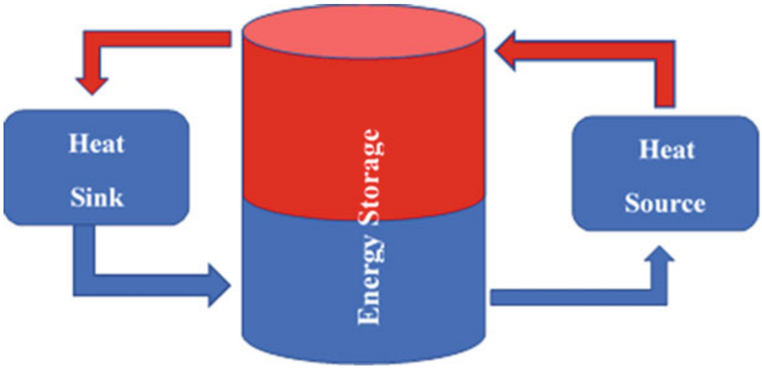

Fig. 3.3 Thermal energy storage tank connected with heat source and sink

By and large, a planned arrangement of activities is required in a few areas of the energy framework for the greatest potential benefits of TES to be figured it out. TES execution models can help in deciding if forthcoming progressed frameworks have execution qualities that make them valuable and alluring and, subsequently, worth seeking after through the high-level turn of events and showing stages.

The benefits of potential TES frameworks should be estimated, in any case, as far as the conditions that are relied upon to exist after innovative work is finished. Care ought to be taken not to apply too restricted a scope of estimates to those conditions. Care additionally ought to be taken to assess specific capacity framework ideas in wording that represents their maximum capacity sway. The adaptability of some TES innovations in various application zones ought to be represented in such appraisals (Kant et al. 2017). Figure 3.3 shows thermal energy storage tank connected with heat source and sink. TES utilization can be understood by observing figure as shown below.

A generous and reliable supply of energy is essential for the present industrial revolution. In general, this is done through heat liberation for the conversion of raw energy into energy that can be regulated. An illustration is heat energy is obtained through wood and coal combustion and then transferred to water to produce steam so it can be used in industrial processes. It is becoming increasingly popular to use electrical energy but to this electricity is derived from burning fossil fuels. When the mismatch between the demand and supply is wider an alternative energy-conversion system should be adopted so that this can convert available energy into the desired form of energy.

In addition to industrial and utility applications, TES has some interesting possibilities. Storage space may be necessary in structures that consume a lot of energy, such as residential and commercial buildings, in order to reduce the peak demand for air conditioning imposed by past electric systems. It would be possible to use TES for replacing these peak loads and similar way many applications can be buffered (Sivasamy et al. 2018). Increasing fuel costs, increasing difficulties in raising capital for expansions of natural gas and nuclear power plants, as well as the emergence of the latest TES technologies, have led to a recent resurgence of interest in these TES methods. Depending on the production cost as well as market demand, energy is a product your power provider values. Energy is valued based on its role in the creation of goods and services, as well as for the convenience and comfort of its consumers. There is no doubt that there will be discussions on the merits of alternative power in the foreseeable future, but for now, energy decisions will be made based on pricing data for various alternative means. The choice between using TES methods or not will appear to be based on prospective cost reductions in either production or consumption unless legislative or regulatory requirements are in place. The prospect of economic viability is among the major considerations that need to be considered for TES systems to become commercially viable (Chavan et al. 2020a).

3.1.3.1 Techniques of Thermal Energy Storage

A high rate of heat transfer makes active heat storage more effective since it is a forced convection heat storage system. Heat transfer into the storage material from a forced convection system identifies an active storage system. During continuous circulation, the medium we store is heated. It is important to note that active energy storage refers to the storage of energy during the day and its use on cloudy days, but passive energy storage uses more light throughout the building to charge and discharge a solid medium. There are two types of active thermal storage: a single tank and a double tank. Heat transfer fluid (HTF) is used for charging and discharging passive storage systems. There is no circulation in the storage medium. Systems with passive storage (also known as regenerators) typically use two mediums. Concrete and castable materials are the main components of passive storage systems.

3.1.4 Energy Demand

Every day, weekly, and at ground level, energy consumption varies in commercial, public, and domestic sectors. Different energy-conversion systems should work together to meet these needs. Peak hour energy generation would be the most costly and hard to supply. Gas turbines and diesel generators are often used to meet peak energy demands, but they are dependent on high-priced and abundant fossil fuels. TES offers an energy solution, one, which is certainly an alternative to peak energy demands. Systems for managing temperature and humidity can improve operation of cogeneration, solar, wind, and hydropower facilities, too. TES can be applied to the following projects:

- Utility: TES systems can be charged during the daytime and can be reutilized in night or off-peak on a regular basis. This will reduce dependence on old-fashioned gas and oil peaking generators during peak periods as the stored energy will be used during these times.

- Industry: Industrial processes can generate high-temperature waste heat that can be utilized to pre-heat as well as to reheat the required components.
- Cogeneration: With a cogeneration system, heat and electricity are closely grouped, and since neither is always needed exactly, extra electricity or heat is stored.
- Solar energy systems: Through TES, rising capacities can be achieved with solar technology methods since TES can store excess energy on sunny days and use it on cloudy or dark days.

3.1.5 Energy Storage Future aspects

Several automotive applications require lighter than current battery packs, which researchers are devoted to making lighter and smaller. For controlling the vehicle temperature TES can be employed over the roof or coating the phase change materials (PCM) all over the vehicle body can minimize battery dependency. Actual heat is used to store energy sources in these working methods. The latent heat of melting salts and paraffins could also be used as a source of thermal energy. Latent storages decrease the amount for the storage space unit by a greater extent but after a few decades of analysis nearly all their problems that are practical still have not been fixed (Singh and Ramadesigan 2017).

The study of TES technology has many encouraging aspects. It is evident that a sustained effort to develop TES is within reach considering the cost gap and, consequently, the potential benefits of TES. There is a possibility that advanced-level TES systems will not be required for several decades with solar energy applications. Solar power usage is likely to grow as more affordable TES options become available in the near future. Some research this is certainly existing development areas into the field of TES tend to be as follows: higher-level TES and transformation systems with phase transformation, chemical, and electrochemical responses; There are several concepts in a TES to generate and to absorb the thermal energy such as thermochemical reactions. Thermochemical reactions are those where two or more chemicals start reacting with heat liberation (Exothermic reaction) or heat absorption (Endothermic reaction).

3.1.6 Energy Storage Methods

The storage element is an essential component of most energy technologies. Among the many examples of fuel that we can use as examples of energy storage, oil stands out as a particularly good one. Fuel, gasoline oil, and petrochemicals are dependable and economically available because of massive quantities of petroleum saved around the world. The Thermal energy storage systems hold transferred heat in a thermodynamically useful form before it is used in other ways. The most common application is the example of storage of domestic and industrial hot water. This may make heating water or steam more convenient, but it is probably not often considered for periods longer than a day. New innovations in storage can sometimes be made possible by advancements in storage and are often an integral part of other new technologies. The most notable benefit of improved storage is solar power. A number this is certainly large of techniques tend to be under development.

A substance's energy can be maintained by increasing or decreasing its temperature by changing its phase (latent energy), or by combining the short-term storage and long-term storage methods. Power technologies tend to create new TES applications of both types. For later use, large- or low-temperature materials may be temporarily stored for later use. Solar power can be stored for nighttime home heat, summertime temperatures for winter use, winter ice for summer cooling, and electrical heat or cool from off-peak hours can be stored for use during peak times in the evening. Like fossil fuels, solar energy is not always available. The cooling loads are also often present after sunset when solar radiation is less where thermal energy supply and demand mismatch can be remedied by TES. TES can take into account the quality of the energy being used as a function of the temperature of the goods that enter, leave, and are stored. A greater range of jobs may be completed using a greater heat method following discharge of the stored thermal energy. Daily, irregular, and seasonal energy demands for manufacturing, commercial, and residential purposes vary widely. Different TES systems must operate synergistically in such diverse sectors, matching carefully to each application that is specifically selected for TES based on their application areas (Chavan et al. 2020b).

In order to understand the optimum potential benefits of thermal energy and other forms of TES, there needs to be a coordinated group of people in many sectors of the energy system.

There are three main types of thermal storage:

1. Sensible thermal energy storage (STES)
2. Latent heat thermal energy storage (LTES)
3. Thermochemical energy storage (TCS).

The most precisely established and familiar mode of storage is sensible thermal storage, followed by latent heat thermal storage which is still under development and demonstration stage and then thermochemical energy storage. Table 3.1 shows the different modes of thermal storage with capacity and efficiency data.

The energy needs of industries, commercial establishments, and the utility sector can differ daily, weekly, or seasonally. TES methods that function synergistically can help match these demands. Applications of TES include air conditioning, room heating, and cooling. With commercial fields becoming increasingly effected by electricity in the last four or five decades, TES practice has evolved into a variety of practices. Such TES systems have actually an enormous potential to help make the using thermal power equipment far better as well as assisting large-scale power substitutions from a perspective that is financial. Generally speaking, a group this is certainly coordinated of in a number of sectors regarding the energy system will

Table 3.1 Different modes of thermal storage with capacity and efficiency data

Type of storage	Development filed	Storage capacity (kWh/ton)	Efficiency (%)
Sensible heat storage	Commercial	10–50	50–90
Latent heat storage	R&D/Demonstration/Commercial	50–150	75–90
Thermochemical storage	R&D only	120–250	75–100

http://energystoragehub.org/technologies/thermal/thermal-storage/

become necessary if the prospective benefits of thermal storage is to be totally realized.

This crucial energy preservation is certainly enabled by numerous types of energy storage. It is possible to save premium fuel costs with energy storage in many industrial processes that produce waste energy that can be recovered. There are different ways in which energy can be stored, but the most feasible means is to transfer it and create it as heat energy, the basis for thermal energy storage systems. This refers to the process of storing energy when it is cooled, heated, melted, solidified, or vaporized; the vital component is the heat released when the method is reversed. Its effectiveness depends on the specific heat capacity (the heat that can be stored in a material when it rises or falls in temperature). A form of TES called latent heat storage occurs when a solid or liquid transitions to a fluid or vapor without noticing any noticeably higher temperature. The main material used in sensible storage techniques is rock, surface, or liquid as the storage medium, and in addition, the heat generated by the storage material is used as a means to store energy. PCMs are used as latent heat storage systems, which allow energy to be stored or released. Generally, PCMs are packaged in tubes, shallow panels, synthetic bags, etc. or are enclosed in wall paneling, ceilings, or other components of conventional buildings (Prasad et al. 2019).

In addition to solar photovoltaic applications, TES also closely works with solar heating systems. There are a number of battery packs on the market today, chilled water storage, hot water storage, and ice storage that fulfill a number of the functions associated with it. Energy storage space applications typically receive direct bonuses from utilities, while high time-of-day prices and needs indirectly encourage consumers to consider these options. Short-term thermal energy storage is generally required for TES since it requires storing large- or low-temperature energy. For instance, TES can store solar power during the day and use it at night, heat during the summer for cold temperatures during the winter, ice during the summer for room cooling, heat created electrically during low-peak hours, and used at peak times (Fredi et al. 2020).

It is impossible to obtain solar energy on a regular basis, unlike fossil fuels. Solar power radiation reaches its peak after sunset, which often coincides with soothing loads. Therefore, solar energy produces heat that seldom escapes into the atmosphere for as long as it takes to heat the item. Because of this, solar energy rarely releases heat directly into the surrounding environment for an extended period of time. Due to this, warm air is rarely released into the surrounding environment until a long time after solar energy has been used. TES will compensate for this mismatch between need and availability. Commercial prosperity and technological competition rely heavily on energy. In order to meet the future's power requirements, it would be helpful to possess a varied range of technologies that can be readily accessed. This is a result of forecasts which are improving and are often imprecise. In addition, the technologies developed should be ones that are environmentally responsible, efficient, and high in quality (Sarbu and Sebarchievici 2018).

As TES is used to reduce complete energy consumption, it conserves petroleum and reduces oil import prices. It is being marketed as an efficient way to reduce the energy needs of the world. After proven performance solves the technical and economic challenges, TES is predicted to become a mainstream option that affects both the manufacturing and commercial sectors potentially resulting in enhanced power efficiency and environmental benefits, among other benefits. We identify TES as a potential method of reducing future peak-power shortages by substantially lowering peak-power demands. A significantly significant portion of our rapidly increasing needs for heating and cooling, particularly for production facilities and commercial entities, can be met by the use of waste heat and climatic power. There are numerous ecological advantages to waste-energy sources as well. There are numerous ecological advantages to waste-energy sources as well. Waste-energy sources have a number of ecological advantages as well. TES technologies have been incorporated into several different kinds and applications. TES are often used in refrigeration and/or for space heating and cooling applications and can be either sensible (oils, molten salts) or latent (ice, phase change materials). Many laboratories are conducting research on TES for its commercial, domestic, and industrial applications around the world (Zhang et al. 2016).

3.2 Thermal Energy Storage Materials

3.2.1 Introduction

In recent year's significant attempts have been put forward for efficient harnessing of different types of energies. Constant escalation in the level of greenhouse gas emissions and hike in fuel costs is the driving force for looking toward thermal energy storage (Kenisarin and Mahkamov 2007). To recover the waste heat energy available new methods and technology have to be developed (Ahmed et al. 2017). Figure 3.4 shows classification of phase change materials.

Reutilization of low-grade available energy from lower temperature range isn't positive due to several technical constraints of grabbing exergy and energy from low-grade heat. Large amount of heat energy is available between 35 and 55 °C from numerous process industries. Various types of thermal energy are stored by changing the energy they contain such as sensible heat, latent heat, and thermochemical storage.

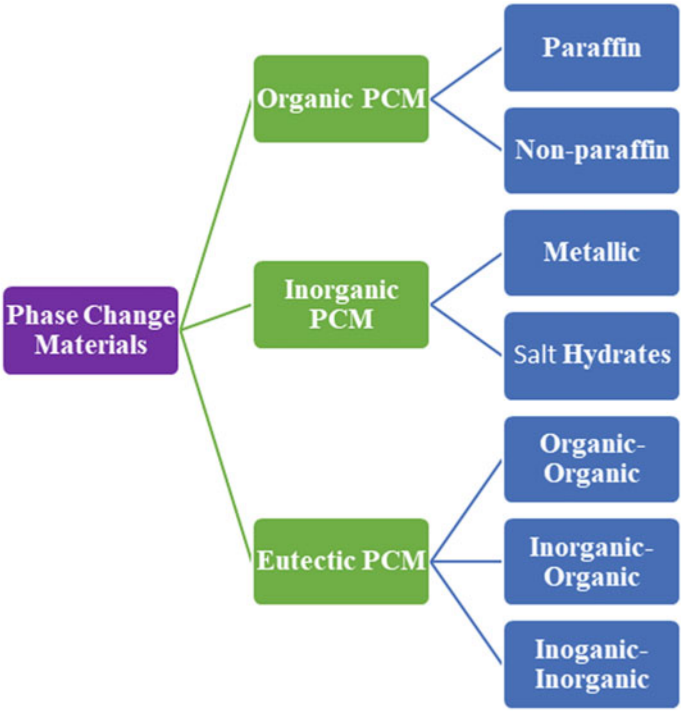

Fig. 3.4 Classification of phase change materials

A thermal storage device's primary component is its material. Materials decide the amount of energy to be stored at given temperature range (Bhatt et al. 2010). These thermal energy storage materials (TESM) are of different characteristics and thermophysical properties which may be suitable for specific kinds of applications. The TESM is divided into various categories based on the mode of heat storage like sensible heat storage materials, latent heat storage materials, and thermochemical storage materials.

These TESMs are further divided into sub-categories based on the medium and mode of heat transfer, like sensible heat can be stored using solid and liquid materials, whereas latent heat-storing materials are phase-changing materials also known as phase change materials. These materials may change their phase after absorbing or rejecting certain amount of heat energy. Also, TESM of low temperature can be divided into different categories depending on the melting point, which makes them suitable for a number of applications such as domestic liquid home heating, direct home heating or heat pump assisted room heating, greenhouse heating, solar cooling, among others. Medium temperature thermal storage (100–180 °C) used for several manufacturing processes, e.g., meals, reports, substance companies, etc. High-temperature storage materials (working temperature range above 900 °C) used for power-plant and metallurgical applications (Akeiber et al. 2016).

The PCMs come to be significant because of its excessive power storage ability, it lowers the fluctuation of temperature through the day period and stabilizes conditions within the range that is required. The limitations of TESM can be eliminated blending with any suitable additive (such as nanoparticles), materials to form composite thermal energy storage materials (CTESM), which allows the material to increase the storage capacity by enhancing their thermophysical properties.

3.2.2 Types of Thermal Energy Storage Materials (TESM)

Depending on the mode of thermal energy storage TESMs are divided into different categories different materials are chosen such as.

1. Sensible heat-storing materials
2. Thermochemical heat-storing materials
3. Latent heat storage materials.

Sensible Heat-Storing Materials These materials don't undergo phase change process only its surface temperature will change with energy absorption. These are probably solids or liquid materials and gaseous materials are not feasible due to their lower storage capacity. Solid materials used for sensible heat storage including metals, metal alloys, concrete, rocks, sand and bricks. These materials are specially used for both high and low-temperature energy storage because they will not boil or freeze. Rocks piles and pebbles are majorly used due to their lower cost and abundantly availability. Rocks are usually made of slackly packed materials and act as porous media which is very efficient for heat transfer. Heating process involves circulation of hot air through the gaps between the rocks, and while cooling process, cold air is circulated. Heat transfer process is more efficient due to availability of larger surface area through which the air interacts with rocks, Concrete and rocks approximately store 36 kJ/kg of energy, at a temperature difference of 50 °C. Liquid sensible heat storage materials also used the best example is domestic solar water heater. Likewise, numerous oils or fluids are used in various industries for storing and reutilizing the waste heat energy available from various processes (Wang et al. 2020).

3.2.3 Thermochemical Heat Storage

Thermochemical heat energy is stored in the form of chemical bonds due to their chemical structure. As per the required applications, whether heating or cooling is required, we can initiate the exothermal or endothermal chemical reaction using some specific chemicals, to break the bonds in their chemical structure which releases large amount of heat energy. Various oxides compounds are used in solar chemical

Table 3.2 Thermal energy storage materials and their working temperature range (Prasad et al. 2019)

S. No.	Materials	Temperature range (°C)
1	Hydroxides	500
2	Iron carbonates	180
3	Metal hydrates	200–300
4	Metal oxides (Ze and Fe)	2000–2500
5	Methane/water	500–1000
6	Methanolation	NA
7	Demethanolation	200–250

reactors, including Fe_3O_4/FeO, MgO/Mg. ZnO/Zn, etc. However, potentiality of thermochemical energy storage is extensively encouraged the researchers to put forward their exertions, but this method is not succeeded due to its inherent limitations, such as chemical stability, durability, long-term reaction reversibility, etc. Table 3.2 shows list of thermochemical energy storage materials with temperature range and change of enthalpy.

3.2.4 Latent Heat Storage Materials/Phase Change Materials (PCMs)

Latent heat storage is the most efficient method of storing heat even at lower temperature ranges. Latent heat storage involves absorption and rejection of heat during phase conversion process, the phase conversion may be solid–solid, solid–liquid, or liquid–gas. Solid–gas phase change materials are impractical for the storage mechanism. Solid–solid phase change involves only internal lattice changes and less efficient to store. Solid–liquid phase change materials are mostly preferable one due to their larger storage capacity. Liquid–gas phase change materials are not preferred due to their larger volume requirements and lower storage capacity (Chavan et al. 2018b).

3.2.5 Classification of Phase Change Materials

In phase change materials, a substance melts and solidifies at certain temperatures. The phase change temperature identifies the temperature at which the change occurs. The selection of suitable PCM for particular range of temperature is important, for different temperature ranges and modes of applications an appropriate material should be selected for achieving superior results.

PCMs are used for both short-term (daily) and long-term (seasonal) energy storage, using different methods and materials. Some of the applications are as follows:

1. Enhancement of thermal energy storage capacity by implementing in gypsum board, plaster, concrete, etc. of the building structure, which can be utilized in peak-load shifting at working temperature range of 22–25 °C.
2. Cold storage applications in cooling plants, especially where the operating temperature range is 7–15 °C.
3. Heat storage in heating systems with working at temperature range of 40–50 °C.
4. Heat storage in solar-based heating and cooling systems working at temperature range of 80–90 °C (Gao et al. 2015).

PCMs are widely classified depending on their thermophysical transformation during heat absorption and rejection capabilities. There are several types of paraffins, most of which have straight hydrocarbon chains as well as small amounts of branching near the end. These are alkanes (C_nH_{2n+2}). The inorganic PCMs are not much preferred due to the effect of supercooling, corrosivity as well as other harmful properties. However, use of paraffin can be complicated because of their leakage and that is undesirable in molten conditions. To reach better storability with safety, 2 or 3 materials are blended to form binary or eutectics which can be ternary also with tailored storage properties. As an example, sodium hydrate (eutectic blend) has more storage density and higher thermal conductivity than paraffin, and it melts and solidifies without accumulation or segregation of component materials.

3.2.6 Characteristics of Phase Change Materials

The PCMs selected for particular applications should possess the abilities as follows.

1. Sustain the operating temperature with correct period transition
2. Possess high latent heat capacity that reduces the size of the storage space
3. High thermal conductivity to make system charge quicker
4. Possess high density that provides better stability in melting and solidification processes
5. The volume requirement should be less and it should not undergo supercooling
6. PCMs should be chemically stable.

3.2.7 Thermal Energy Storage Materials and their Properties

Since TES materials have different inherent properties, they each have different advantages and disadvantages. Some properties with their desirableness are listed in Table 3.3.

Table 3.3 Classification of TESM with their desirable and undesirable properties

Material	Type	Desirable properties	Undesirable properties
Organic materials	Paraffins	Non-corrosive	Lower thermal conductivity
		Chemically steady up to 500 °C	Not suitable with plastic container
		Less expensive	Moderately flammable
		Reliable	
		Safe and predictable	
	Non paraffins	High heat of fusion	Inflammability
		No supercooling	Low thermal conductivity
		Fatty acids are preferred for low-temperature heat storage applications	Low flashpoints
			Variability at higher temperatures
Inorganic materials	Salt Hydrate	Specific heat capacity is high	Contaminated
		Higher thermal conductivity	Needs supercooling
		Phase change volume is small	
		Anti-corrosive	
		Companionable with plastics	
	Metallic	Higher thermal conductivity	Specific heat capacity is less
		Lower specific heat capacity	Vapor pressure is low

3.2.8 Composite Thermal Energy Storage Materials

The provision of thermal energy storage using composite thermal energy storage materials is among the best methods of enhancing the thermophysical properties of PCMs. These materials are able to deliver excellent and appealing results with various compositions of different base materials and additives. A wide range of thermal storage applications benefits from materials with high storage capacity. Researchers continuously finding new ways to enhance the storage capacity increase the efficiency of the TES systems. One of the ways is to prepare tailored materials for specific applications with desired characteristics, by enhancing the desired characteristics and reducing undesired properties. For example, advancement of specific properties such as low thermal conductivity, supercooling and incongruent melting, will significantly influence the TES system performance.

3.2.9 *Effect of Nano-additives on Thermal-Physical Properties Enhancement*

Composite materials are the next hope for the future energy storage technology. Achieve better thermal storage performance with any single material is a very difficult and hence any suitable materials can be blended with different combinations of materials. Some of the composite materials with different additive materials are listed below to understand how these different additives affect the base material properties. Table 3.4 shows effect of nano-additives on thermophysical properties of TESMs with different combinations.

3.2.9.1 Conclusions and Future Trends

Sensible heat storage is appropriate to domestic water heating systems, district heating, and industrial requirements. A well-known commercial heat storage medium is considered to be water, due to its thermophysical properties and availability, with large number of domestic and industrial applications. In large-scale applications, underground storage of sensible heat is preferable, which utilizes both liquids and solids; however, the long-term storage of sensible heat imposes limitations on the method and is limited. Moreover, sensible heat storage systems necessitate proper design and fabrication. Phase change materials overcome the limitations of sensible heat storage and offer a higher storage capacity with the latent heat storage mode.

Phase change materials also allow to focus on a particular discharge temperature which is generally phase change temperature of the specific material. The most important properties of phase change materials are melting temperature, latent heat of fusion, and thermophysical properties which greatly influence the storage capacity. Most of the literature is attentive on repetitive and marketed materials such as paraffin. It is suggested to focused on composite materials with a wide working temperature range such as paraffins as base materials and carbon-based nanomaterials are most suitable combination for various applications. Since composite materials also suffer with some limitations like lower thermal reliability, phase-segregation, and subcooling issues which need to be studied intensely.

In future greenhouses, thermal energy storage systems can be combined with heating/cooling or humidification/dehumidification processes and also can be attached to poly-generation systems. Further research can be conducted on finding the possible candidate materials for different modes of storage that can be extensively implemented in a more cost-effective method.

Table 3.4 TESM's with different combinations of nano-additives

Refs.	TESMs combination		Constraints analyzed	Result
	Base materials	Blends		
Tang et al. (2016)	Lithium and Sodium carbonates (43%) and (57%), respectively	MgO and CNTs*	Thermal conductivity (K) and thermal storage density (TSD)	$K = 4.3$ (W/m K), TSD = 530 kJ/kg
Bailey (2010)	Na_2CO_3/MgO	MWCNTs*	TES, and constancy	Enhanced*
André et al. (2016)	Polyurethane	Graphene*	Thermal and chemical stability	Enhanced*
Zhou et al. (2014)	GA (30%) and MA (70%)	Graphite and silver iodide (0.5 wt%)	Heat of fusion	Enhanced up to 34%
Ye et al. (2014)	PEG	Acrylic polymers*	K and TSD	Enhanced*
Pielichowska et al. (2016)	PEG	Cellulose and GNPs (5.3 wt%)	K, and enthalpy	K enhanced by 463%
Paul et al. (2015)	MA	PA and SL*	Thermal stability	Enhanced*
Torkkeli (2003)	Sodium and potassium nitrate (60:40)	Alumina nanoparticle (0.78%)	Specific heat	Improved up to 30.6%
Yang et al. (2016a)	Paraffin wax	CNTs (S-MWCNTs), L-MWCNTs, CNFs, and GNPs (5wt%.)	K	K enhanced 164%
Fan et al. (2013)	PDMS	PDMS–G–NF *	Enthalpy	65.72% Enhanced
Wang et al. (2016)	SA	EG*	K	K enhanced by four folds
Şahan and Paksoy (2017)	PA-SA	GnPs and EG*	K	K enhanced 2.7 folds
Zheng (1995)	OA	GA*	K	K enhanced 14 folds
Audichon et al. (2017)	n-Tricosane	GNFs*	Phase change	Solidification time reduced by 61%
Yuan et al. (2016)	Paraffin wax	NG*	K	K enhanced 70%
Sanusi et al. (2011)	Epoxy	Graphene oxide and graphene*	Thermo-mechanical properties	Enhanced*
Arthur and Karim (2016)	Aluminate cement paste	Nano-MgO (NM) and Polycarboxylate*	K	K enhanced 40.8%

(continued)

Table 3.4 (continued)

Refs.	TESMs combination		Constraints analyzed	Result
	Base materials	Blends		
Yuan et al. (2014)	Paraffin	Cu nanoparticles (1 wt%*)*	Phase change characteristics	Melting time abridged by 13.1%
Liu et al. (2017a)	Clathrate hydrates	Water*	Thermal characteristic	Enhanced*
Ferrão (2017)	Paraffin	Water*	Heat transfer mechanism	Heat release rate (HRR) enhanced 25%
Wang et al. (2017)	Water	Octadecane*	TSD	*Cp* condensed
Liu et al. (2017b)	Water	Copper nanoparticles*	Phase change characteristics	Shorten the melting time*
Pina et al. (2017)	Fatty acid	EG*		
Xu et al. (2016)	Paraffin	Alumina nanoparticles (3–8%)		
Wu et al. (2012)	$Ba(OH)_2 \cdot 8H_2O$	Cu nanoparticles*	Heat transfer rate	Enhanced*
Delgado et al. (2012)	$NaNO_3$	Porous copper matrix*	Heat transfer characteristics	*K* and HRR improved*
Rao et al. (2012)	Water	CuO nano particles*	Phase change characteristics	Melting period reduced*
Khodadadi and Hosseinizadeh (2007)	$CaCl_2–6H_2O$	Cu, Al_2O_3 and CuO nanoparticles*	Energy capacity	Energy consumption condensed 43%
Lu et al. (2014)	$NaNO_3/KNO_3$	Metallic foam and sponge*	*K*	Enhanced*
Lv et al. 2016a)	Erythritol	EG *	Thermal properties	Melting time condensed 16.7%
Parsazadeh and Duan (2017)	Water	Copper nanoparticles*		*K* and HRR Improved*
Yang et al. (2018)	Paraffin wax	xGnP-1 and xGnP-15*		
Alkan (2006)	Docosane And Hexacosane	Sulfuric Acid*		

(continued)

Table 3.4 (continued)

Refs.	TESMs combination		Constraints analyzed	Result
	Base materials	Blends		
Jegadheeswaran et al. (2012)	Hydrated salt	Micro-copper particles*		
Karaipekli et al. (2017)	Eicosane (C20)	CNTs (1 wt%)	*K*	*K* enhanced 113.3%
Wang et al. (2014)	OP10E (30%)/water (70%)	Graphite nanoparticles (5 wt%)	*K*	*K* improved*
Li et al. (2017)	Paraffin (*RT 42*)	EG Powder (20 wt%)	*K* and TSD	*K* enhanced 7.5 folds
Lee et al. (2016)	Epoxy	Graphene*	Thermal characteristics	Enhanced*
Yang et al. (2016b)	Paraffin	Copper foam*		Abridges melting time*
Lv et al. (2016b)	Paraffin	Kaolin*	*K*	TSD and HRR enhanced*
Lv et al. (2016c)	Polyethylene glycol	EG*	Thermal characteristics	Enhanced TSD 46.52%,
Luo et al. (2015)	Paraffin			Condense melting time*

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