REVIEW ON THERMAL ENERGY STORAGE SYSTEMS

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ABSTRACT
In the past five thousand years human energy consumption per capita has risen from 9 to 230 kWh/capita.day. At the current rate of usage, taking into consideration population increases, natural resources will be depleted within a few decades. One must therefore endeavour to take precautions today for a viable world for coming generations. There are many situations where available energy is wasted because it is in the wrong place and/or at the wrong time. Therefore, there is a desperate need for energy storage and a very wide range of techniques is used for this purpose. Most methods involve high capital investment; however, so a cheaper alternative has been widely exploited in which thermal energy is stored in a suitable medium. Sensible and latent heat thermal storage systems in general have been among main topics in research for the last two decades or so, but although the information is quantitatively enormous, it is also widely spread in the literature, and often quite difficult to find. This work provides a survey of studies dealing with thermal energy storage (TES) using sensible and solid–liquid phase change thermal energy storage units. Three aspects have been the focus of this review: storage media, heat transfer analysis and applications. The work described below falls within an area of international interest as it deals with energy saving, the efficient and rational use of available resources and the optimum use of renewable energies.

KEYWORDS: Energy storage, Porous media, Phase change materials, Solar energy, Fixed beds.

1. Introduction

Energy production and consumption is the main driving force of all urban and industrial activities. More than 80% of world energy is provided by combustion of fossil fuels. In addition, 16% of the total energy consumption is provided by nuclear power and the remaining 4% includes other forms, such as hydro, wind and solar energy.

There are many situations where available energy is wasted because it is in the wrong place and/or at the wrong time. There is therefore a need for energy storage and a very wide range of techniques is used for this purpose including electrical storage, air compression and the pumped storage of water. All such methods involve high capital investment; however, so a cheaper alternative has been widely exploited in which thermal energy is stored in suitable medium. Efforts of rational and effective energy management as well as environmental considerations increased the interest in utilizing renewable energy sources, especially solar energy. The work described below falls within an area of international interest as it deals with energy saving, the efficient and rational use of available resources and the optimum use of renewable energies [8]. Within this framework, thermal energy storage (TES) provides solutions in very specific areas:

- The time delay between production or availability of energy and its consumption in receiving systems,
- Security of energy supply (hospitals, computer centers, etc.)
- Thermal inertia and thermal protection

This work provides a survey of studies dealing with TES using sensible and phase change materials. The material in this review has been arranged within the main areas of work:

- Energy storage media
- Heat transfer analysis
- Applications

Useful classification of the substances used for TES is shown in Figure.1. The latter contains a complete review of the material types which have been used, their classification, characteristics, advantages and disadvantages and the various experimental techniques used to determine the behavior of these materials in melting and solidification [16].

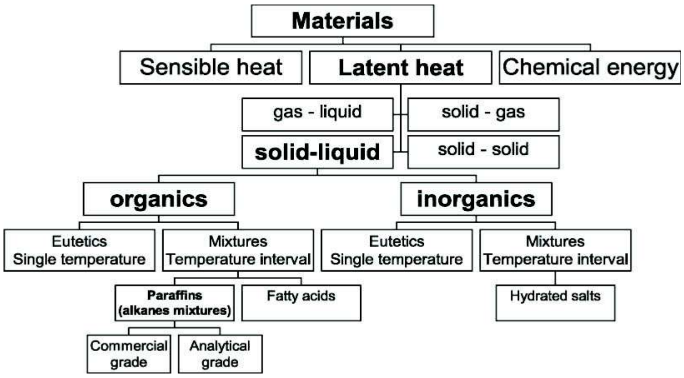

Fig.1: Classification of energy storage materials [16]

Basically, there are three methods of storing thermal energy, i.e. thermo-chemical, sensible and latent.

2. Sensible heat storage

In a sensible heat storage unit, thermal energy is stored by changing the temperature of the storage medium, which can be a liquid or a solid. The amount of energy stored in the unit depends on heat capacity of the medium, temperature changes and the amount of the storage material. Thus, it is desirable for the storage medium to have high specific heat capacity, long term stability under thermal cycling, compatibility with its containment and, most importantly, low cost. Sensible heat storage may be classified on the basis of the heat storage media as liquid media storage such as water, oil based fluids, molten salts etc. and solid media storage like rocks, metals and others.

2.1. Liquid media storage

Heat storage liquids are plentiful and economically competitive. The pros and cons of some selected media are given below.

- At low temperature water is one of the best storage media. It has higher specific heat than other liquids, and it is cheap and widely available. However, due to its high vapor pressure, it requires costly insulation and pressure withstanding containment for high temperature applications. Water can be used over a wide range of temperature, say 25-90 °C. Water storage tanks are made from a wide variety of materials, like steel, aluminum, reinforced concrete and fiber glass. The tanks are insulated with glass wool, mineral wool or polyurethane. Their sizes vary from a few hundred liters to a few thousand cubic meters [9].
- Solar ponds offer a simple and economical method for collecting and storing large amounts of solar energy in the form of low temperature thermal energy (50-95 °C).
- Petroleum based oils and molten salts are the most proposed substitutes for water. Their heat capacities are 25-40% of that of water on a weight basis. However these substitutes have lower vapor pressure than water and can operate at high temperatures exceeding 300 °C. The oils are limited to less than 350 °C due to stability and safety reasons and can be quite expensive [11].

2.2. Solid media storage

For low as well as high temperature thermal energy storage, solid materials such as rocks, metals concrete, sand, bricks etc., can be used. In this case, energy can be stored at low or high temperatures since these materials will neither freeze nor boil [19].

The difficulties of the high vapor pressure of water and the limitations of other liquids can be avoided by storing thermal energy as sensible heat in solids. Pebble beds or rock piles are generally used as a storage material due to their low cost.

The pebble bed or rock pile consists of a bed of loosely packed rock material through which the heat transport fluid can flow as shown in figure 2. The thermal energy is stored in the porous bed by forcing heated air into the bed and recuperated again (later) by re-circulating ambient air into the previously heated bed.

The energy stored in a packed bed storage system depends on several parameters, such as rock size and shape, voidage (porosity) in the bed and thermo-physical properties of the heat transfer fluid and the bed material [4-6].

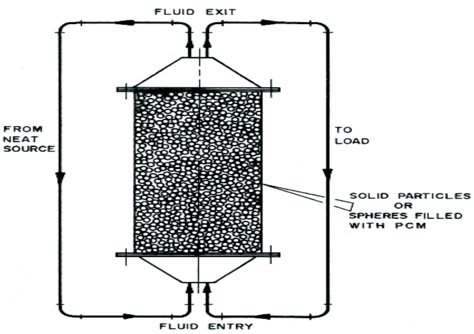

Fig.2: General Layout of fixed bed storage units [5]

Solar energy can be stored in insulated vessels of rocks or pebbles, and it is convenient for use in buildings. This type of storage is used very often for temperatures up to 100 °C in conjunction with solar air heaters. Typically, the characteristic size of the pieces of rock used is in the range 1-5 cm. An approximate rule followed for sizing is to use 300-500 kg of rock by m^2 of solar collector area for space heating applications. For a temperature change of 50 °C, rocks and concrete can store up to 36 kJ/kg [14].

2.3. Storage in metals

Most of the materials proposed for high temperature (120-1400 °C) energy storage are either inorganic salts or metals. Among the metals, aluminum, magnesium and zinc have been mentioned as suitable examples. The use of metals media may be advantageous where high thermal conductivity is required and where cost is of secondary priority [20].

2. Latent heat storage

In the latent heat storage, thermal energy is accumulated by means of a reversible change phase occurring in the medium. Solid-liquid transformation is most often used to avoid large pressure vessels required for vaporization or sublimation [2]. Latent heat storage is a particularly attractive technique, since it provides a high energy storage density and has the capacity to store as latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the phase change materials (PCMs). This means that a much smaller weight and volume of material is needed to store a certain amount of energy [22].

PCMs may undergo solid-solid, liquid-gas or solid-liquid phase transformations. Relatively few solid-solid PCMs have been identified that have heats of fusion and transition

temperatures suitable for thermal storage applications. Liquid-gas PCMs usually have high heats of transformations, however, due to their large volume change during transition, they are not usually considered for practical applications. Solid-liquid PCMs are useful because they store a relatively large quantity of energy over a narrow temperature range, without a corresponding large change in volume [24].
Typically, the chosen PCM is placed in long thin tubes stacked in a container. During a heating cycle, the collected solar heat from the collector is circulated through narrow spaces between the tubes and melts the PCM by storing the sensible heat as well as the latent heat of fusion. During the heat recovery cycle, the circulation of cool air would pick up the stored energy from the PCM and transport it to the heat load. Therefore, the latent heat storage system uses the sensible heat in the solid and liquid phases and additionally the latent heat due to the phase change of the storage media.
The development of any latent heat thermal energy storage (LHTES) system, therefore, involves an understanding of two essentially diverse subjects: heat storage materials (or PCMs) and heat exchangers [17].

Table.1 shows a comparison between the sensible heat storage using a rock bed and water tank and also shows the latent heat storage using organic and non-organic compounds. The advantage of the latent heat over the sensible heat is clear from the comparison of the volume and mass of the storage unit required for storing a certain amount of heat. It is also clear from Table.1 that inorganic compounds have a higher volumetric thermal storage density than the most of the organic compounds due to their higher latent heat and density [11].
Through the comparison between the sensible and latent energy storage units, one can conclude that the latter solution is more appealing. In fact, the latent heat of most materials is much higher than their sensible heat, thus requiring a much smaller mass of storage medium for storing and then recovering a given amount of thermal energy. Moreover, the latent heat thermal storage process occurs at nearly constant temperature, which is typically desirable for efficient operation of most thermal systems.

Tab.1: Comparison between the different methods of heat storage [11]

Property	Rock	Water	Organic PCM	Inorganic PCM
Density (kg/m^3)	2240	1000	800	1600
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Latent heat (kJ/kg)		—	190	230
Latent heat (kJ/m^3)			152	368
Storage mass for 10^6 J(kg)	67,000	16,000	5300	4350
Storage volume for 10^6	30	16	6.6	2.7
Relative storage mass	15	4	1.25	1.0
Relative storage volume	11	6	2.5	1.0

4. Phase change materials

4.1. Recommended properties of PCMs

The PCM to be used in the design of thermal storage system should possess desirable thermo-physical, kinetic and chemical properties, which may be recommended as follows:

- Melting temperature in the desired operating temperature range,
- High latent heat of fusion/unit volume so that the required volume of the container to store a given amount of energy is smaller,
- High specific heat in order to provide additional significant sensible heat storage,
- High thermal conductivity of both solid and liquid phases in order to assist the charging and discharging energy of the storage system,
- Small volume change on phase transformation and low vapor pressure at operating temperature in order to reduce the containment problem,
- High rate of crystal growth, so that the system can meet demand of heat recovery from the storage system,

- Complete reversible freeze/melt cycle,
- No degradation after a large number of freeze/melt cycles,
- No corrosiveness to the construction materials,
- Non-toxic, non-flammable and non-explosive material for safety.

Depending on the applications, the PCMs should first be selected based on their melting temperature. Materials that melt below 15 °C are used for storing coolness in air conditioning applications, while materials that melt above 90 °C are used for absorption refrigeration. All other materials that melt between these two temperatures ($15°C<\theta_m<90°C$) can be applied in solar heating and for heat load leveling applications [10]. These materials represent the class of materials that has been studied most.

4.2. Stability of thermal properties under extended cycling

The most important criteria that have limited widespread use of latent heat stores are the useful life of PCMs–container systems and the number of cycles that can withstand without any degradation in their properties. Insufficient long term stability of the storage materials is mainly due to two factors: *poor stability* of the materials properties due to thermal cycling, *and/or corrosion* between the PCM and the container.

The development of PCM containers must be directed towards demonstration of physical and thermal stability, as the PCMs must be able to undergo repetitive cycles of heating and cooling. The purpose of these thermal cycling tests is to determine whether these thermal exposures will result in migration of the PCM or may affect the thermal properties of the PCM.

4.3. Heat transfer coefficient enhancement

One relatively cheap way of storing energy, particularly from air streams, is to use a bed of a granular material. The key parameter in the design of such a system is the heat transfer coefficients between the heat transfer fluid (HTF) and the bed material.

Considerable research has been done on heat transfer in packed beds for thermal energy storage, with interests ranging from theoretical to experimental investigations [2, 3].

In these studies, it was observed that reliable heat transfer correlations for high-temperature packed bed were hard to come by in the literature. Most of the developed correlations were limited to relatively low temperature ranges and with spherical particles. In the development of the gas-pellet heat transfer Nusselt number correlation, it was noticed that all the related existing correlations are functions of Reynolds and Prandtl numbers [11].

Successful utilization of PCM heat-transfer media depends on developing means of containment or encapsulation. Several different techniques have been studied for encapsulating heat sink chemicals in plastic or metal matrices. These can be divided into three categories on the basis of the size of the encapsulated particle.

- Micro-encapsulation of emulsion-sized particles,
- Encapsulation of granules,
- Macro-encapsulation of large blocks or shapes.

Encapsulation results in the improvement of the physical and chemical stability of the heat sink material, fabrication of encapsulated structures would facilitate production of modular heat storage units and useful structural or architectural materials would be developed. The most cost-effective containers are plastic bottles and tin-plated food cans. However, corrosion could lead to disastrous consequences if internal and external lacquer finishes are not applied properly to the mild steel can.

There are many advantages of microencapsulated PCMs, such as:

- Increasing heat transfer area,
- Reducing PCMs reactivity towards the outside environment,
- Controlling the changes in the storage material volume as phase change occurs.

4.4. Classification of PCMs

The various PCMs are generally divided into **three** main groups: organic, inorganic and eutectics of organic and/or inorganic compounds.

4.4.1. Organic PCMs

Organic compounds include paraffin and non-paraffin organics. They present several advantages such as no corrosiveness, low or no under cooling, possess chemical and thermal stability, ability of congruent melting, self-nucleating properties and compatibility with conventional materials of construction.

Technical grade paraffin has been extensively used as heat storage materials due to wide melting/solidification temperature ranges and has a relatively high latent heat capacity. They also have no sub-cooling effects during the solidification as well as small volume change during the phase-change process. They are chemically stable, nontoxic and non-corrosive over an extended storage period [12].

Widely used non-paraffin organics, as latent heat storage materials are fatty acids like lauric, myristic, palmitic and stearic acid. Their advantages are a possibility for reproducible melting/solidification behavior and little or no sub-cooling effects. Disadvantages of organic compounds include lower phase-change enthalpy, low thermal conductivity and inflammability [7].

4.4.2. Inorganic PCMs

Inorganic compounds include salt hydrates, salts, metals and alloys. The main advantages of inorganic compounds are a high volumetric latent heat storage capacity, often twice the capacity of organic compounds and high thermal conductivity. However, they suffer from decomposition and super-cooling which further can affect their phase change properties.

A number of salt hydrates such as sodium sulfate decahydrate (Glauber's salt), calcium chloride hexahydrate, sodium thiosulfate pentahydrate, sodium acetate trihydrate and barium hydroxide octahydrate, were investigated largely.

Major problems with most of the salt hydrates are super-cooling, phase segregation, corrosion and lack of thermal stability. Super-cooling in several salt hydrates has been prevented by adding nucleating agents or by promoting nucleation by rough container walls or using the cold finger technique. Tables 2 and 3 show some thermo-physical properties of some organic and inorganic PCMs.

4.4.3. Eutectics

Eutectics are mixtures of two or more salts which have definite melting–freezing points. Their behavior is analogous to congruent melting salt hydrates and has great potential for thermal energy storage application. A large number of eutectics of inorganic and organic compounds have been reported, and they can be classified as inorganic eutectics, organic eutectics and organic–inorganic eutectics. Some of the eutectics are listed in Tables 4 and 5.

Tab.2: Inorganic substances with potential use as PCM [7]

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
$KF \sim 4H_2O$	18.5	231	n.a.	1447 (liquid, 20 °C) 1455 (solid, 18 °C) 1480
$Mn(NO_3)_2 \sim 6H_2O$	25.8	125.9	n.a.	1738 (liquid, 20 °C) 1728 (liquid, 40 °C) 1795 (solid, 5 °C)
$CaCl_2 \sim 6H_2O$	29	190.8	0.540 (liquid, 38.7 °C)	1562 (liquid, 32 °C)
	29.2	171	0.561 (liquid, 61.2 °C)	1496 (liquid)
	29.6	174.4	1.088 (solid, 23 °C)	1802 (solid, 24 °C)
	30	192		1710 (solid, 25 °C)
$Na_2SO_4 \sim 10H_2O$	32.4	254	0.544	1485 (solid)
	32	251.1		1458
$Na_2HPO_4 \sim 12H_2O$	35.5	265	n.a.	1522
	36	280		
	35	281		
$Mg(NO_3)_2 \sim 6H_2O$	89	162.8	0.490 (liquid, 95 °C)	1550 (liquid, 94 °C)
	90	149.5	0.502 (liquid, 110 °C)	1636 (solid, 25 °C)
$MgCl_2$	714	452	n.a.	2140
NaCl	800	492	5	2160

Tab.3: Organic substances with potential use as PCM [7]

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Paraffin $_{C16–C18}$	20–22	152	n.a.	n.a.
Paraffin $_{C13–C24}$	22–24	189	0.21 (solid)	0.760 (liquid, 70)C) 0.990 (solid, 20 °C)
Poly-glycol E600	22	127.2	0.189(liquid, 38.6 °C)	1126 (liquid, 25 °C)
	n.a.	n.a.	0.187 (liquid, 67 °C)	1232 (solid, 4 °C)
Paraffin $_{C18}$	28	244	0.148 (liquid, 40 °C)	0.774 (liquid, 70 °C)
	n.a.	n.a.	0.15 (solid)	n.a.
	27.5	243.5	0.358 (solid, 25 °C)	0.814 (solid, 20 °C)
Paraffin wax	64	173.6	0.167(liquid, 63.5 °C) 0.346 (solid, 33.6 °C) 0.339 (solid, 45.7 °C)	790 (liquid, 65 °C) 916 (solid, 24 °C)
Naphthalene	80	147.7	0.132 (liquid, 83.8 °C) 0.341 (solid, 49.9 °C)	976 (liquid, 84 °C) 1145 (solid, 20 °C)

n.a.: not available.

Tab.4: Inorganic eutectics with potential use as PCM [12]

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/ m^3)
66.6% $CaCl_2$ ~ $6H_2O$+33.3% $MgCl_2$ ~ $6H_2O$	25	127	n.a.	1590
48% $CaCl_2$+4.3% NaCl+0.4% KCl+47.3 ~ H_2O	26.8	188	n.a.	1640
61.5 % $Mg(NO_3)_2$ ~ $6H_2O$ + 38.5 % NH_4NO_3	52	125.5	0.494 (liquid, 65 °C) 0.515 (liquid, 88 °C) 0.552 (solid, 36 °C)	1515(liquid, 65 °C) 1596(solid, 20 °C)
11.8% NaF+54.3% KF+26.6% LiF+7.3% MgF_2	449	n.a.	n.a.	2160 (liquid)
60% $Na(CH_3COO)$ ~ $3H_2O$ +40% $CO(NH_2)$	31.5	226	n.a	n.a
	30	200.5	n.a	n.a

Tab.5: Organic eutectics with potential use as PCM [12]

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)
37.5% Urea+63.5 acetamide	53	n.a.	n.a.
67.1% Napthalene+32.9% benzoic acid	67	123.4	0.136 (liquid, 78.5 °C) 0.130 (liquid, 100 °C) 0.282 (solid, 38 °C) 0.257 (solid, 52 °C)
Lauric–capric acid	18	120	n.a.
Lauric–palmitic acid	33	145	n.a.
Lauric–stearic acid	34	150	n.a.

% in weight.
n.a.: not available.

4.4.4. Organic/inorganic materials

A comparison of the main advantages and disadvantages of organic and inorganic materials is shown in Table.6.

Tab.6: Comparison of organic and inorganic materials for heat storage [10]

Organics	Inorganics
Advantages	***Advantages***
No corrosives Low or none under-cooling Chemical and thermal stability	Greater phase change enthalpy
Disadvantages	***Disadvantages***
Lower phase change enthalpy Low thermal conductivity Inflammability	Under-cooling Corrosion Phase separation Phase segregation, lack of thermal stability

5. Some geometrical configurations and applications of heat storage units

The application of energy storage with sensible and phase change materials is not limited only to solar energy heating and cooling but has also been considered in other applications. Some are discussed in the following sections.

5.1. Aquifers thermal energy storage

For large scale storage applications, underground natural aquifers have been considered. Aquifers are geological formations containing ground water, offering a potential way of storing heat for relatively long periods of time. For example, 10^5 m^3 of aquifer material can store about 3 MJ of heat for each 10 °C temperature difference. This type of storage is well suited for seasonal storage. The attractiveness of aquifer storage is due to its low cost characteristics, its high input/output rates and its large capacity. Because of its bulk nature, aquifer storage is not feasible for small loads, such as individual houses.

Aquifers hold great promise for underground energy storage, assuming that ones adequate for such storage can be found. In many systems, the heat source for aquifer thermal energy storage (ATES) is solar collectors. Several large-scale projects related to high-temperature underground storage (>50 °C) of waste heat from co-generation plants and incineration plants are in planning in Europe and the US [13, 23, 25]. Estimation of the heat recovery rate is required before the system is built.

5.2. Solid media sensible heat storage for parabolic trough power plants

For parabolic trough power plants using synthetic oil as the heat transfer medium, the application of solid media sensible heat storage is an attractive option regarding investment and maintenance costs. Solid media sensible heat storage materials have been widely researched in parabolic trough plants. For the development of solid media storage material, the thermo-physical properties of the materials like density, specific heat capacity, thermal conductivity, coefficient of thermal expansion (CTE) and cyclic stability as well as availability, cost and production methods are of great relevance.

A high heat capacity reduces the storage volume and a high thermal conductivity increases the dynamics in the system. The CTE of the storage material should match the CTE of the embedded metallic heat exchanger material. A high cyclic stability is important for a long storage unit lifetime [15].

5.3. Indirect contact latent heat storage of solar energy

Extensive efforts have been made to apply the latent heat storage method to solar energy systems, where heat is required to be stored during the day for use at night. The studies varied from those related to the fundamental aspects of heat transfer to those in which the PCM is tested in full size heat storage units.

Most PCMs have low thermal conductivity that limits heat transfer rates during their applications. Hence, the PCM must be encapsulated in such a way as to prevent the large drop in heat transfer rates during its melting and solidification. The PCM is usually contained in a number of thin flat containers, similar to plate type heat exchangers, as shown in Figure.3.

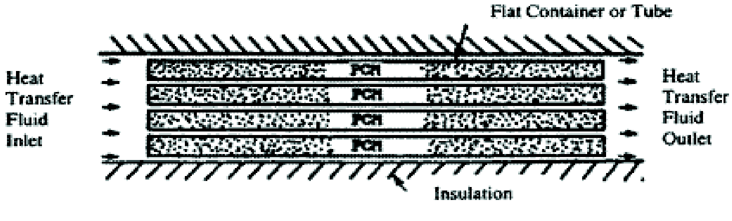

Fig .3: Schematic of a L.H.S unit using flat containers for encapsulating the PCM [26].

Alternatively, it may be contained in small diameter tubes with the heat transfer fluid flowing along or across the tubes. The idea of using finned tubes in which the PCM was placed between the fins has also been tested. Although a significant improvement in heat transfer rate was found, the high cost of the finned tubes may make their use uneconomical [26]. It is to be noted that such arrangements may improve heat transfer rates significantly only when a liquid is used as a heat transfer fluid. In air based systems, the heat transfer coefficients of both the air and the PCM sides are low [7, 8].
A large improvement in the heat transfer rate was obtained by encapsulating the PCM in small plastic spheres to form a packed bed storage unit. However, the expected high pressure drop through the bed and its initial cost may be major drawbacks of such units. Most of the PCMs undergo large changes in volume (~10%) during melting. This may cause high stresses on the heat exchanger walls. Volume contraction during solidification may not only reduce heat transfer area but also separate the PCM from the heat transfer surface and increasing the heat transfer resistance dramatically. The problem is usually minimized by proper selection of the containers, which should be partially filled with the PCM. Spherical encapsulation can be a good solution to this problem.
In an effort to improve the performance of phase change storage units, Farid et al [9] have suggested the use of more than one PCM with different melting temperatures in a thin flat container, as shown in Figure.4.

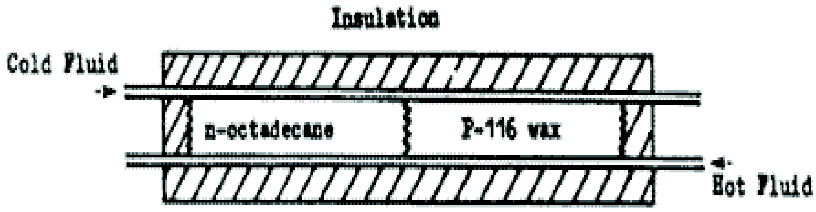

Fig.4: Simplified sketch of a thermal storage unit employing two types of PCM [9]

5.4. Spiral thermal energy storage unit

The use of a vertical spiral heat exchanger in a latent heat energy storage system has been analyzed experimentally. A spiral heat exchanger, commonly used in chemical and food industries, seems to be a good candidate for this task. Compactness, enhanced heat transfer due to centrifugal forces, easy sealing, large heat transfer surface and a shorter undisturbed low length are the most appealing features of such a choice [1]. The thermal energy storage units are usually designed as a vertical cylindrical heat exchanger of Archimedes spiral geometry. It is shown in Figure.5 in its isometric view. This is achieved by winding two sheets of a copper plate into the form of a spiral; two coaxial spiral cylinders are created.

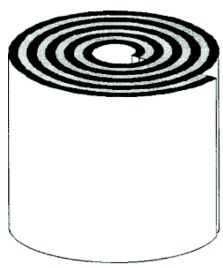

Fig.5: Isometric view of a vertical cylindrical STES unit [1]

5.5. Combined sensible and latent heat storage system

The sensible heat storage (SHS) system is simple and a well-developed technology. Latent heat storage (LHS) systems using phase change material (PCM) as storage medium offer advantages such as high heat storage capacity, small unit sizes and isothermal behavior during charging and discharging processes. But these types of systems are not in commercial use as much as SHS systems because of the poor heat transfer rate during heat storage and recovery processes. The main reason is that during phase change, the solid–liquid interface moves away from the convective heat transfer surface (during charging in cool storage process and discharging in hot storage process) due to which the thermal resistance of the growing layer of solidified PCM increases, thereby resulting in poor heat transfer rate.

The combined sensible and latent systems eliminates the difficulties experienced in the SHS and LHS systems to some extent and posses the advantages of both systems.

It is understood from the literature survey that most of the research work on TES is concerned only with either SHS systems or LHS systems and not much work has been reported on combined sensible and latent systems. The thermal behavior of packed beds of *combined* sensible and latent heat TES system integrated with constant temperature water bath/solar flat plate collector has been studied. The packed bed contains encapsulated PCM in spherical capsules, which are surrounded by SHS material. The performance of these systems during discharging process is also compared with the conventional SHS system [18].

5.6. Phase change thermal storage for shifting the peak heating load

Electricity consumption varies during the day and night according to the demand by industrial, commercial and residential activities. The variation in electricity demand sometimes leads to a differential pricing system in peak and off peak periods, usually after midnight until early morning. The shift of electricity usage from peak periods to off peak periods will provide significant economic benefit. The development of an energy storage system may be one of the solutions to the problem when electricity supply and demand are out of phase. Energy storage systems will enable the surplus energy to be stored until such time as it is released when needed.

Winter storage heating is a direct and a simple application of energy storage and has been used in many countries. The most common domestic storage heater uses ceramic bricks and structural cement, which is heated with electrical heating wires or heat transfer fluids (such as hot water) during the night. During the day, the heat is extracted from the heater by natural convection and radiation or by forced convection using an electric fan. Farid and Hasnain [9, 10] have introduced a new concept to the design of these storage heaters by replacing the ceramic bricks with a paraffin wax encapsulated in thin metal containers. During heat charge, the wax stores a larger amount of heat than the latent heat of melting, which is continuously discharged during the other periods.

5.7. Building applications

The selection of PCMs to meet residential building specifications has received minor attention, although it is one of the most foreseeable applications of PCMs. The ability to store thermal energy is important for effective use of solar energy in buildings. Because of the low thermal mass of lightweight building materials, they tend to have high temperature fluctuations, which result in high heating and cooling demands. It has been demonstrated that paraffins, as mixtures of several linear alkyl hydrocarbons, may be tailored by blending to obtain the desired melting point required for a particular application. Pure paraffins with exceptionally good properties have not yet been tested further due to the unavailability of inexpensive bulk sources. In buildings, a more interesting approach to smooth the temperature variations within a space is by using wallboards containing a PCM. The wall large heat transfer area supports large heat transfer between the wall and the space. The wallboards are cheap and widely used in a variety of applications, making them very

suitable for PCM encapsulation. However, the principles of latent heat storage can be applied to any appropriate building materials.
Heat storage is applicable to both new and existing buildings and can be integrated with both air and water distribution systems. Building mass and structure cement can also be used with active or passive storage design. The most common configuration using building mass for thermal storage is floor warming. Heating and cooling of buildings were widely investigated using their floor. Solar radiation stored in the floor thermal mass was found to reduce heating energy consumption significantly (30% or more) [14, 21]. Figure.6 shows a general layout of a standard solar air space-heating system. However, the development of reliable and practical thermal energy storage systems still faces some major hurdles, such as uncertainties concerning the long term thermal behavior and the small number of PCMs suitable for room temperature applications.

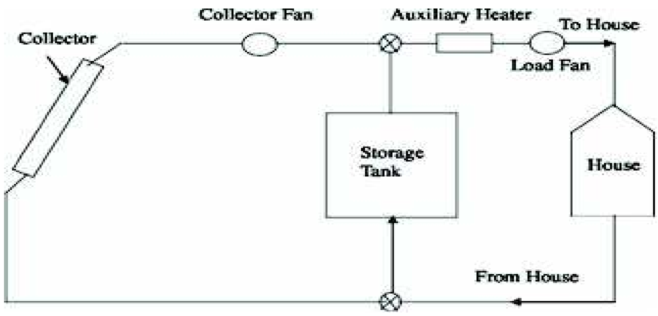

Fig .6: Schematic representation of a standard solar air space-heating system [14]

6. Conclusions

The following may be established as conclusions:

- Sensible heat storage and latent heat storage are among the major techniques of thermal energy storage considered nowadays for different applications, such as space heating and hot water production,
- The operation of packed beds for energy storage depends mainly upon efficient heat transfer coefficient between the fluid stream and the medium in the bed,
- Most existing heat transfer correlations for the packed bed thermal energy storage are limited to relatively low temperature ranges and with spherical particles,
- Latent heat storage is a developing technology that has been found quite promising in recent times. In the development of this field, research is underway in two axes, namely the investigation of phase change materials (PCM) and of heat exchangers,
- Solid-liquid PCMs are useful because they store a relatively large quantity of energy over a narrow temperature range, without a corresponding large change in volume during transition,
- The PCMs must undergo thermal cycling tests in order to determine whether these thermal exposures will result in migration of the PCM or may affect the thermal properties of the PCM,
- Encapsulation results in the improvement of the physical and chemical stability of the heat sink material, increases heat transfer area, reduces PCMs reactivity towards the outside environment,
- Spherical capsules are preferred due to favorable ratio of volume of energy stored to the area of heat transfer and also because of easiness of packing into the storage tank with good bed porosity,
- Organic and inorganic compounds are the two most common groups of PCMs,

- Most organic PCMs are non-corrosive, chemically and thermally stable; exhibit little or no sub-cooling and low vapor pressure. Their disadvantages are low thermal conductivity, high changes in volume on phase change and flammability,
- Inorganic compounds have a higher volumetric thermal storage density than the most of the organic compounds due to their higher latent heat and density,
- Inorganic compounds have a high thermal conductivity, non-flammable and low cost in comparison to organic compounds; however they are corrosive to most metals and suffer from decomposition,
- There is a clear advantage of the latent heat over the sensible heat from the comparison of the volume and mass of the storage unit required for storing a certain amount of heat,
- Despite that PCMs have been widely investigated by many researchers, many of their thermo-physical properties in the solid and liquid phases are lacking in the literature. It is suggested that further detailed calculations and experimental data for these properties should be made in order to assist the effective and appropriate design of the thermal storage units.

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