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Comparison of Thermal Energy Storage Techniques

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Abstract: Various types of energy storage techniques are reviewed and their performances in storing energy compared in this study. Water storage systems required very large volume for large heat storage capacities and corrosion problem for long operation periods. There is also stratification problem and due to this controls are required. Scale formation is another problem with such systems. With packed-bed storage there is no corrosion or scale forming problem but volume of the system might increase with an increase in cost. On the other hand, by the use of phase change storage systems, large volumes required by the other two types are eliminated because of the bond interaction of the storage material and the container, storage material looses its energy storage characteristics after a period of time.

Key words: Energy storage, techniques, water storage, packed-bed storage, phase change storage

INTRODUCTION

Developing efficient and inexpensive energy storage devices is as important as developing new sources of energy. The Thermal Energy Storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. The TES is not a new concept and it has been used for centuries. Energy storage can reduce the time or rate mismatch between energy supply and energy demand and it plays an important role in energy conservation. Energy storage improves performance of energy systems by smoothing supply and increasing reliability. For example, storage would improve the performance of a power generating plant by load leveling. The higher efficiency would lead to energy conservation and improve cost effectiveness. Some of the renewable energy sources can only provide energy intermittently. Although, the sun provides an abundant, clean and safe source of energy, the supply of this energy is periodic following yearly and diurnal cycles, it is intermittent, often unpredictable and diffused. Its density is low compared with the energy flux densities found in conventional fossil energy devices like coal or oil-fired furnaces. The demand for energy, on the other hand, is also unsteady following yearly and diurnal cycles for both industrial and personal needs. Therefore, the need for the storage of solar energy cannot be avoided. Otherwise, solar energy has to be used as soon as it is received. In comparison, the present yield in energy gained by fossil fuels and waterpower amounts to about 70×1012 kWh. But, the technical use of solar energy presently poses problems primarily because of inefficient collection and storage. One of the important characteristics of a storage system is the length of time during, which energy can be kept stored with acceptable losses. If solar energy is converted into a fuel such as hydrogen, there will be no such a time limit. Storage in the form of thermal energy may last for very short times because of losses by radiation, convection and conduction. Another important characteristic of a storage system is its volumetric energy capacity, or the amount of energy stored per unit volume. The smaller the volume, the better is the storage system. Therefore, a good system should have a long storage time and a small volume per unit of stored energy. If mass specific heat capacity is not small, denser materials have smaller volumes and correspondingly an advantage of larger energy capacity per unit volume. The space available is limited both in transport and in habitat applications. The volume occupied by the present available storage systems is considerable and may be an important factor in limiting the size of storage provided. The amount of energy storage provided is dictated by the cost. The cost of floor space or volumetric space should be one of the parameters in optimizing the size of storage.

The technology of thermal energy storage has been developed to a point, where it can have a significant effect on modern life. The major nontechnical use of thermal storage was to maintain a constant temperature in dwelling, to keep it warm during cold winter nights. Large stones, blocks of cast iron and ceramics were used to store heat from an evening fire for the entire night. With the advent of the industrial revolution, thermal energy

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storage introduced as a by-product of the energy production. A variety of new techniques of thermal energy storage have become possible in the past. A major application for thermal storage today is in family dwellings. Heat storage at power plants typically is in the form of steam or hot water and is usually for a short time. Very recently, other materials such as oils having very high boiling point, have been suggested as heat storage substances for the electric utilities. Other materials that have a high heat of fusion at high temperatures have also been suggested for this application. Another application of thermal energy storage on the electric utilities is to provide hot water. Perhaps, the most promising application of thermal energy storage is for solar heated structures and almost any material can be used for thermal energy storage.

THERMAL ENERGY STORAGE SYSTEMS AND APPLICATIONS-OVERVIEW

The storage of thermal energy is very important to many engineering applications. For example, there is a need for waste heat recovery systems for systems where the waste heat availability and utilization times are different. Similarly, for systems such as solar heat collectors, there needs to be an effective medium, in which to store the energy for night usage or even on cloudy days. An effective review on some of the main storage mediums can be found in Hasnain (1998). As expected, there are two main types-sensible and latent systems. Sensible systems harness the specific heat of materials, which include both liquid and solid materials. Latent systems store thermal energy in the form of a change in phase and do not require vast temperature differences to store thermal energy and can be stored in a variety of Phase Change Materials.

The first-law efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the storage to the energy stored into it where, mC is the total heat

$$\eta = \frac{mC(T - T_0)}{mC(T_\infty - T_0)} \quad (1)$$

capacity of the storage medium and T, T_0 are the maximum and minimum temperatures of the storage during discharging, respectively and T is the maximum temperature at the end of the charging period. Heat losses to environment between the end of discharging and the beginning of the charging periods, as well as during these processes are neglected. The first law efficiency can have only values <1.

Two particular problems of thermal energy storage systems are the heat exchanger design and in the case of phase change materials, the method of encapsulation. The heat exchanger should be designed to operate with as low a temperature difference as possible to avoid inefficiencies.

If one tries to get an overview of heat storage systems one would be overwhelmed by the large number of possible technical solutions and the variety of storage systems. Latent heat thermal energy storage systems, using phase change materials to store heat or coolness, have many applications.

The specific application, for which a thermal storage system is to be used determines the method to be adopted. Some of the considerations, which determine the selection of the method of storage and its design are as follows:

- The temperature range, over which the storage has to operate
- The capacity of the storage has a significant effect on the operation of the rest of the system. A smaller storage unit operates at a higher mean temperature. This results in a reduced heat transfer equipment output as compared to a system having a larger storage unit. The general observation, which can be made regarding optimum capacity is that short-term storage units, which can meet fluctuations over a period of 2 or 3 days, have been generally found to be the most economical for building applications
- Heat losses from the storage have to be kept to a minimum. Heat losses are particularly important for long-term storage
- The rate of charging and discharging
- Cost of the storage unit: This includes the initial cost of the storage medium, the containers and insulation and the operating cost.

Other considerations include the suitability of materials used for the container, the means adopted for transferring the heat to and from the storage and the power requirements for these purposes. A figure of merit that is used occasionally for describing the performance of a storage unit is the storage efficiency, which is defined by Eq. 1. The time period over which this ratio is calculated would depend upon the nature of the storage unit. For a short-term storage unit, the time period would be a few days, while for a long-term storage unit it could be a few months or even 1 year. For a well-designed short-term storage unit, the value of the efficiency should generally exceed 80%. Table 1 shows an overview of thermal energy storage methods.

Table 1: Overview of thermal energy storage methods

Type of thermal energy storage	Functional principle	Phases	Examples
Sensible heat	Temperature change of the medium with highest possible heat capacity	Liquid Solid	Hot water, organic liquids, molten salts, liquid metals
Latent heat	Essentially heat of phase change	Liquid-solid	Nitrides, Chlorides, Hydroxides, Carbonates, Fluorides, Euctectics
		Solid-solid	Hydroxides

LATENT TES SYSTEMS

In latent heat storage the principle is that when heat is applied to the material, it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapour as latent heat of vapourization. When, the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapor to liquid. The latent heat of transformation from one solid phase into another is small. Solid-vapor and liquid-vapor transitions have large amounts of heat of transformation, but large changes in volume make the system complex and impractical. The solid-liquid transformations involve relatively small changes in volume. Such materials are available in a range of transition temperatures. Heat storage through phase change has the advantage of compactness, since the latent heat of fusion of most materials is very much larger than their enthalpy change for 1 K or even 0 K. For example, the ratio of latent heat to specific heat of water is 80, which means that the energy required to melt 1 kg of ice is 80 times more than that required to raise the temperature of 1 kg of water 1°C. Any latent heat thermal energy storage system should have at least the following three components: a suitable Phase Change Material (PCM) in the desired temperature range, a containment for the storage substance and a suitable heat carrying fluid for transferring the heat effectively from the heat source to the heat storage. Furthermore, the PCMs undergo solidification and therefore cannot generally be used as heat transfer media in a solar collector or the load. Many PCMs have poor thermal conductivity and therefore require large heat exchange area. Others are corrosive and require special containers. Latent heat storage materials are more expensive than the sensible heat storage media generally employed, like water and rocks. These increase the system cost. Due to its high cost, latent heat storage is more likely to find application when:

- High energy density or high volumetric energy capacity is desired, e.g., in habitat where space is at a premium, or in transportation where either volume or weight must be kept to a minimum
- The load is such that energy is required at a constant temperature or within a small range of temperatures
- The storage size is small. Smaller storage has higher surface area to volume ratio and therefore, cost of packing is high

Compactness is then very important in order to limit the containment costs. Similarly, heat losses are also more or less proportional to the surface area. Compactness is also, an important factor to limit the heat losses in storage of small capacities. Latent TES systems have become much more viable for a high volumetric heat capacity. Usually, latent systems can store much more thermal energy for a given volume, require less of a temperature gradient and can be used for both hot and cold thermal energy storage, depending on the material. A comprehensive review of the various types of systems can be found in Sharma and Sagara (2007) where, various applications and PCM innovations are discussed. Briefly, some of these applications include space heating and cooling, solar cooking, greenhouse upkeep, solar water heating and waste recovery systems. However, it is the design, control and analysis of these systems, which researchers are most concerned with. As examples, a solar water heating system utilizing encapsulated PCM, an ice-on-coil laboratory unit and an encapsulated ice industrial refrigeration system are presented, as well as past and present methods for system optimization.

Latent solar-water heating systems are a perfect example of the advantage of thermal energy stored in PCMs. Nallusamy *et al.* (2006) study the performance of a solar collector, coupled with a storage tank filled with encapsulated PCMs, which in this case is paraffin. Water is used as the heat transfer fluid and the inlet temperature to the storage tank was varied to study the effects of bed porosity and flow rate on overall system performance. It was found that the latent storage system drastically reduced the size of the solar heat storage system and that these systems are best used for intermittent usage where, the latent heat can be best used.

Lee and Jones (1996) studied an ice-on-coil TES unit perfect for residential and light commercial conditions. The chiller, a vapor compression refrigeration cycle using Refrigerant R22, freezes the water inside the evaporator tubes during charging, for the purpose of extraction during peak energy times. The unit was tested varying both evaporator and condenser temperatures and parameters such as the ice-building rate, the compressor power, cooling rate, heating rate, energy efficiency ratio and power consumption factor are studied. The results indicate that among other things, the energy efficiency increased with a decreased condenser temperature. The energy efficiency is also readily calculable and heat transfer rates are easily obtainable, which is an encouraging aspect of many TES systems, when attempting to minimize energy losses.

An encapsulated ice refrigeration system is studied in Cheralathan *et al.* (2007). Henze (2003) presents an overview of the control for central cooling plants with ice TES. The control algorithms target the minimization of energy usage and minimizing demand costs, to name a few. Fully optimal control, based on full system knowledge, is also introduced. The main arguments here state that depending on the specific objectives of the system, a control algorithm can be utilized, which optimizes the objectives in a concise manner. Henze (2005) furthers this by investigating the relationships between cost savings and energy consumption associated with the conventional control of typical TES systems. Items accounted for in these optimizations include varying fan power consumption, as well as chiller and storage coefficient of performance. The results indicate that buildings can be operated in such a manner as to reduce overall costs, with only a small increase in total energy consumption.

Another interesting application of PCMs is the regulation of indoor temperatures, when rapid changes occur in the surrounding outdoor temperature. Khudhair and Farid (2004) discuss, among other latent TES applications, the advantages of PCMs installed in concrete, gypsum, wallboards, ceilings and floors to limit the effects of outdoor temperature swings on indoor temperatures. These PCMs can act as a heat source, while solidifying during cooler indoor temperatures, or a heat sink, when melting during warmer indoor temperatures, by having a fusion point close to that of room temperature. Latent TES by means of solar energy and peak load shifting by running a refrigeration cycle are also discussed, as are many other advantages and typical drawbacks of these systems.

It has been conventional, as has been done in the above works, to use energy consumption, energy efficiency and cost minimization as the main benchmarks in determining optimal system configurations. However, in recent years, a new approach has been exercised, which simultaneously reduces both energy and cost inputs. These exergy analysis have been the preferred method of late to better analyze the performance of these systems, as well as the location and severity of energy losses. Dincer and Rosen (2002) discuss the usefulness of exergy analysis in the performance and optimization of various TES systems. During exergetic analysis of aquifer, stratified storage and cold TES systems, appropriate efficiency measures are introduced, is the increasing importance of temperature, especially during cold TES.

Rosen *et al.* (1999) provide detailed exergy analysis of many types of cold TES systems. They consider full cycles of charging, storage and discharging in both sensible and latent systems. The results indicate that exergy clearly provides a more realistic and accurate measure of the performance of a cold TES system, since it treats cold as a valuable commodity. This is in contrast to the energy analysis, which treats cold as an undesirable commodity. In addition, it was summarized that the exergy analysis is substantially more useful than the energy analysis. Furthering this study, Rosen *et al.* (2000) examine an industrial sized encapsulated ice TES unit during full charging, discharging and storage cycles. The results indicate that in addition to energy analysis being incomplete for cold TES, they also, achieve misleadingly high efficiency values.

For the system in question, the overall energy efficiency was 99.5%, while the exergy efficiency was calculated to be 50.9%. This solidifies the fact that exergy analyses allow for a more complete diagnostic of cold TES systems and the locations of their shortfalls.

SENSIBLE THERMAL ENERGY STORAGE SYSTEMS

In the case of sensible heat storage systems, energy is stored or extracted by heating or cooling a liquid or a solid, which does not change its phase during this process. A variety of substances have been used in such systems. These include liquids like 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.

The choice of the substance used depends largely on the temperature level of the application, water being used for temperature below 100°C and refractory bricks being used for temperatures around 1000°C. Sensible heat storage systems are simpler in design than latent heat or bond storage systems. However, they suffer from the disadvantage of being bigger in size. For this reason, an important criterion in selecting a material for sensible heat storage is its (ρC_p) value. A second disadvantage associated with sensible heat systems is that they cannot store or deliver energy at a constant temperature. We will first take up for consideration the various materials used.

Performance of a THS is characterized by storage capacity, heat input and output rates, while charging and discharging and storage efficiency. The storage capacity of an SHS with a solid or liquid storage medium is given by:

$$Q_S = m\,C\Delta T = V\rho\,C\Delta T \quad (2)$$

Where,

m = Mass
V = Volume
c = Specific heat,
ρ = Density
ΔT = $T_{max} - T_{min}$

is maximum temperature difference between maximum and minimum temperatures of the medium. This expression can be used to calculate the mass and volume of storage material required to store a given quantity of energy.

For a packed bed used for energy storage, the porosity of the bed must be taken into consideration and neglecting the heat capacity of the energy transferring medium in the storage the volume of the packed bed storage is written as:

$$V = Q_S/P\,C\,(1 - \varepsilon)\,\Delta T \quad (3)$$

where, ε is the porosity of the packed bed. The storage energy density per unit mass and the storage energy density per unit volume are, respectively defined as:

$$q = Q_S/m = C\,(T_{max} - T_{min}) \quad (4)$$

and

$$q = Q_S/V = \rho C\,(T_{max} - T_{min}) \quad (5)$$

The review of works in sensible. Thermal Energy Storage systems is interesting to note. Sensible thermal storage is possible in a wide number of mediums, both liquid and solid. Liquid media for thermal storage include oils, water, molten salts, etc., while solid media are usually in the form of rock, concrete or metals and can include alloys such as zirconium oxide for extreme temperatures (Nsofor, 2005). There are a number of works regarding both cases, though here we will consider two short examples, a solar pond and a rock bed, both designed for solar energy storage.

Karakilcik *et al*. (2006) perform an interesting performance investigation of a solar pond in Adana, Turkey. The pond was filled with salty water to form three zones of varying density, which do not mix. The upper zone is the freshwater layer at the top of the pond and is fed by rainwater and feed water to compensate for water lost by evaporation. The middle layer, called the insulation zone, is designed to keep the freshwater zone and the lower zone from mixing, while absorbing solar energy in the form of heat. The lower zone, which is the densest mixture, retains the most heat and absorbs the most heat from the sun, contains the heat exchangers to the solar pond and exchanges heat with both the bottom of the solar tank as well as the insulation zone. As expected, the highest thermal efficiencies of the system came in mid summer, when solar and ground radiation levels are at their highest and temperature gradients are quite low.

A performance investigation of a solar air heater connected to a rock bed thermal storage device is considered by Choudhury *et al*. (1995). A two-pass, single cover solar air heater is coupled to the rock bed, while operational parameters and geometric design are varied in order to study the effect on efficiency. Factors such as charging time, rock bed size, individual rock size, air velocity and void fraction are studied, as are the effects on thermal efficiency of the system. It was found that the charging time had the most significant effect on the overall efficiency, with the optimal charging time set at 8 h for this particular location in New Delhi.

Liquid storage media: With its highest specific heat water is the most commonly used medium in a sensible heat storage system. Most solar water heating and space heating systems use hot water storage tanks located either inside or outside the buildings or underground. The sizes of the tanks used vary from a few hundred liters to a few thousand cubic meters. An approximate thumb rule followed for fixing the size is to use about 75-100 L of storage per square meter of collector area. Water storage tanks are made from a variety of materials like steel, concrete and fiberglass. The tanks are suitably insulated with glass wool, mineral wool or polyurethane. The thickness of insulation used is large and ranges from 10-20 cm, because of this, the cost of the insulation represents a significant part of the total cost and mean to reduce this cost have to be explored. Shelton has shown that in an underground tank, the insulating value of the earth surrounding the tank may be adequate and this could provide the bulk of the insulation thickness required. However, it may take as much as one year for the earth around a large storage tank to reach a steady state by heating and drying and a considerable amount of energy may be required for this purpose. If the water is at atmospheric pressure, the temperature is limited to 100°C. It is possible to store water at temperature a little above 100°C by using pressurized tanks. This has been done in a few instances. In order to reduce the costs, an alternative way, which is being examined for large-scale storage, is to use naturally occurring confined underground aquifers, which already contain water as

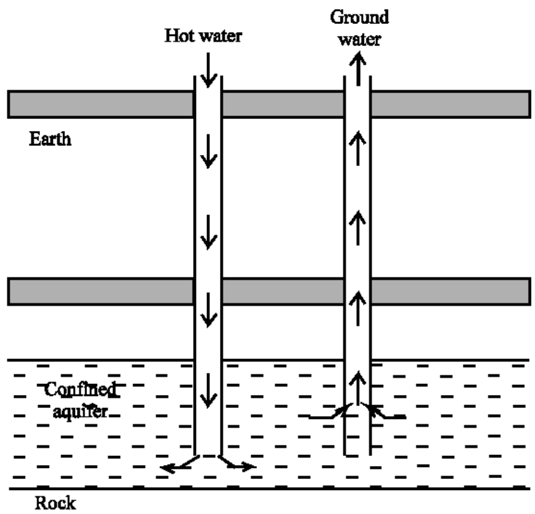

Fig. 1: Underground sensible energy storage system

shown in Fig. 1. It is proposed to pump the hot water to be stored into such aquifers, thereby displacing the existing cold ground water. Since, the investment required is a series of openings for injecting and withdrawing water, it is expected that storage costs for such systems would be low. Heat transfer oils are used in sensible heat storage systems for intermediate temperatures ranging from 100-300°C. Some of the heat transfer oils used for this purpose are Dowtherm and Therminol. The problem associated with the use of heat transfer oils is that they tend to degrade with time. The degradation is particularly serious if they are used above their recommended temperature limit. The use of oils also presents safety problems since, there is a possibility of ignition above their flash point, for this reason, it is recommended that they be used in systems with an inert gas cover. A further limitation to the use of heat transfer oils is their cost. For this reason, they can be seriously considered for use only in small storage systems. A few molten inorganic salts have been considered for high temperatures (300°C and above). One is a eutectic mixture of 40% $NaNO_2$, 7% $NaNO_3$ and 53% KNO_2 (by weight) and is available under the trade name of 'Hitec'. Hitec has a low melting point of 145°C and can be used up to a temperature of 425°C. Above this temperature decomposition and oxidation begin to take place. Another molten salt being considered for high temperature storage is sodium hydroxide, which has a melting point of 320°C and could be used for temperatures up to 800°C. However, it is highly corrosive and there is difficulty in containing it at higher temperatures. Water, being inexpensive and widely available can be effectively used to store sensible heat. The advantages and disadvantages of such storage can be summarized as follows:

Advantages:

- Water is inexpensive, easy to handle, non-toxic, non-combustible and widely available
- Water has a comparatively high specific heat and high density
- Heat exchangers may be avoided if water is used as the heat carrier in the collector
- Natural convection flows can be utilized when pumping energy is scarce
- Simultaneous charging and discharging of the storage tank is possible
- Adjustment and control of a water system is variable and flexible

Disadvantages:

- Water might freeze or boil
- Water is highly corrosive
- Working temperatures are limited to <100°C and often have to be far below this boiling temperature
- Water is difficult to stratify.

Freezing and corrosion problems can be met by using chemical additives. Water sometimes remains economically competitive at higher temperatures despite the need for pressure containment especially so when it is stored in aquifers. Organic oils, molten salts and liquid metals circumvent the problems of vapor pressure, but have other limitations in handling, containment, cost, storage capacities, useful temperature range, etc. These limitations can be noticed in the Table 2. In spite of the fact that these fluids have been used in commercial operations, the lifetime and cost requirements for solar thermal storage limit their use in applications such as space heating. However, oils and molten salts have been utilized in solar thermal power plants.

Solid storage media: Energy can be stored in rocks or pebbles packed in insulated vessels. This type of storage is used very often for temperatures up to 100°C in conjunction with solar air heaters. It is simple in design and relatively inexpensive. Typically, the characteristic size of the pieces of rock used varies from 1-5 cm. An approximate rule of thumb for sizing is to use 300-500 kg of rock/m^2 of collector area for space heating applications. Rock or pebble-bed storage can also be used for much higher temperatures up to 1000°C. Presently, most thermal storage devices use sensible heat storage and a good technology is developed for the design of such systems. However, above 100°C, the storage tank must be able to contain water at its vapor pressure and the storage tank cost rises sharply for temperatures above this point. Organic oils molten salts and liquid metals do not exhibit the same pressure problems, but their use is limited

Table 2: Properties of liquid media for sensible heat storage

Medium	Fluid type	Temp. range (°C)	Density (kg m^{-3})	Heat capacity (J/kg/K)	Thermal conductivity (W/m/K)
Water	-	0 to 100	1000	4190	0.63 at 38°C
Water-ethylene glycol 50/50	-	-	1050	3470	-
Caloria HT43	Oil	-10 to 315	-	2300	-
Dowtherms	Oil	12 to 260	867	2200	0.112 at 260°C
Therminol 55	Oil	-18 to 315	-	2400	-
Therminol 66	Oil	-9 to 343	750	2100	0.106 at 343°C
Ethylene glycol	-	-	1116	2382	0.249 at 20°C
Hitec	Molten salt	141 to 540	1680	1560	0.61
Engine oil	Oil	Up to 160	888	1880	0.145
Draw salt	Molten salt	220 to 540	1733	1550	0.57
Lithium	Liquid salt	180 to 1300	510	4190	38.1
Sodium	Liquid salt	100 to 760	960	1300	67.5
Ethanol	Organic liquid	Up to 78	790	2400	-
Propanol	-	Up to 97	800	2500	-
Butanol	-	Up to 118	809	2400	-
Isobuthanol	-	Up to 100	808	3000	-
Isopentanol	-	Up to 148	831	2200	-
Octane	-	Up to 126	704	2400	-

Table 3: Solid media properties for sensible heat storage

Medium	Density (kg m^{-3})	Specific heat (J/kg/K)	Heat capacity $\rho c \times 10^{-6}$ (J/m^3/K)	Thermal conductivity (W/m/K)	Thermal diffusivity $\alpha = k/\rho c\ 10^6$ (m^2/s)
Aluminum	2707	896	2.4255	204 at 20°C	84.100
Aluminum oxide	3900	840	3.2760	-	-
Aluminum sulfate	2710	750	2.0325	-	-
Brick	1698	840	1.4263	0.69 at 29°C	0.484
Brick magnesia	3000	1130	3.3900	5.07	1.496
Concrete	2240	1130	2.5310	0.9 – 1.3	0.356-0514
Cast iron	7900	837	6.6123	29.3	4.431
Pure iron	7897	452	3.5694	73.0 at 20°C	20.450
Calcium chloride	2510	670	1.6817	-	-
Copper	8954	383	3.4294	385 at 20°C	112.300
Earth (wet)	1700	2093	3.5581	2.51	0.705
Earth (dry)	1260	795	1.0017	0.25	0.250
Potassium chloride	1980	670	1.3266	-	-
Potassium sulfate	2660	920	2.4472	-	-
Sodium carbonate	2510	1090	2.7359	-	-
Stone, granite	2640	820	2.1648	1.73 to 3.98	0.799-1.840
Stone, limestone	2500	900	2.2500	1.26 to1.33	0.560-0.591
Stone, marble	2600	800	2.0800	2.07 to 2.94	0.995-1.413
Stone, sandstone	2200	710	1.5620	1.83	1.172

because of their handling, containment, storage capacities and cost. Between liquid materials, water appears to be the most convenient because it is inexpensive and has a high specific heat. The difficulties and limitations relative to liquids can be avoided by using solid materials for storing thermal energy as sensible heat. But, larger amounts of solids are needed than using water, due to the fact that solids, in general, exhibit a lower storing capacity than water. The cost of the storage media per unit energy stored is, however, still acceptable for rocks. Direct contact between the solid storage media and a heat transfer fluid is necessary to minimize the cost of heat exchange in a solid storage medium. The use of rocks for thermal storage provides the following advantages:

- Rocks are not toxic and non flammable
- Rocks are inexpensive
- Rocks act both as heat transfer surface and storage medium
- The heat transfer between air and a rock bed is good, due to the very large heat transfer area and the effective heat conductance of the rock pile is low, due to the small area of contact between the rocks. Then, the heat losses from the pile are low

Magnesium oxide (magnesia), aluminum oxide (alumina) and silicone oxide are refractory materials and they are also suitable for high-temperature sensible heat storage. Concrete and bricks made of magnesia have been used in many countries for many years for storing heat. They are available in the form of devices with electric heater elements embedded in the bricks. The heat is stored at night (when electricity rates are low) by switching on the electric heaters and is supplied during the day for space heating purposes by allowing air to pass through the devices. Below, the properties of solid media storage are shown in Table 3.

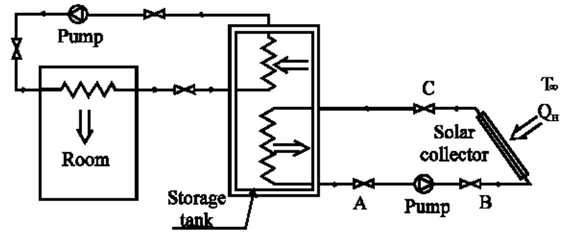

Fig. 2: Schematic diagram of the solar energy storage system

Solar energy storage systems: Concrete is a relatively good medium for heat storage in passively heated or cooled houses. It is also, considered for application in intermediate-temperature solar thermal plants. Consider the thermal energy storage system shown schematically in Fig. 2. The system consist of a large liquid bath of mass m and specific heat C placed in an insulated vessel. The system also, includes a collector to give the collector fluid a heat gain and a room, in which this heat gain is discharged.

Operation of the system takes place in three steps; charging, storage and removal processes. At the beginning of the storage process, valves A, B, C are opened. Hot fluid from the collector at temperature T_{is} enters the system through valve C. This hot collector fluid is cooled while flowing through the heat exchanger 2 immersed in the bath and leaves at the bottom of the system at temperature T_{es}. The heat carrying liquid is then pumped to the collector with the help of pump 2. The fluid entering the collector takes QH from the sun and its temperature increases to T_{is} and the storage cycle is completed. While, the hot gas flowing through the heat exchanger 2, the bath temperature T_b and fluid exit temperature of storage process T_{es} approach the hot fluid inlet temperature of storage process T_{is}. The heating process is allowed to continue up to the desired storage material (water) temperature. At that desired moment the valves A-C are closed. After the storage periods D-F are opened, so the removal process begins. Cold fluid with constant mass flow rate flows through valve F and gets into the heat exchanger 1 and it receives energy from the liquid bath then leaves the system through valve D. This heated fluid is then pumped to the radiator to give heat to the medium (room) and the removal cycle is completed. The system includes two controlling units to control the fluid temperatures. One of them is located at the collector outlet. This unit measures the temperature of the fluid at the collector outlet and compares it with the temperature in the tank. If the tank temperature is higher than the collector outlet temperature it stops the pump 2 automatically. The other controlling unit is located at the radiator outlet. If the radiator outlet temperature is higher than the tank temperature, it stops the pump 1 automatically.

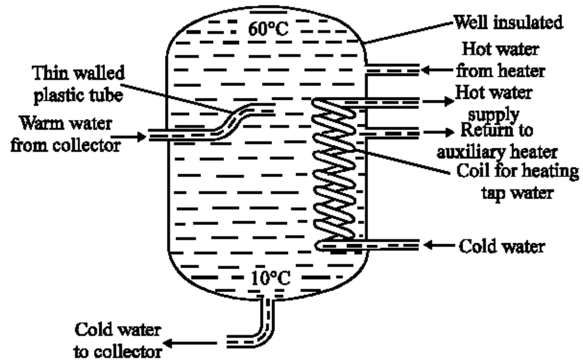

Fig. 3: Thermally stratified hot liquid tank

Thermal stratification and its capability to store exergy: Improvement in storage is actually achieved by thermal stratification that is, water of a high temperature than the overall mixing temperature can be extracted at the top of the container and water of a lower temperature than the mixing temperature can be drawn off from the bottom to make use even of short insolation periods and thus, running the collector at a higher efficiency. In practice, perfect stratification is not possible since the water entering the tank will cause a certain amount of agitation and mixing.

Moreover, there would be a certain amount of diffusion from the entering water (to the stored water) before it reaches the appropriate density level. Having obtained good thermal stratification by eliminating mixing, it is equally important to maintain the temperature layers. Due to the heat losses from the surface of the storage tank, the temperature of water near the vertical walls is lower, leading to natural convection currents that destroy the temperature layers. In order to maintain stratification over long time intervals, the tank should be provided with extremely good thermal insulation or with special installations. An idea in assisting thermal stratification is, for example, the use of a thin plastic tube of the same density as the water as shown in Fig. 3. The tube moves up and down according to the density of the hot water, placing the warm water in the right part of the tank. In the case of thermal stratification in storage, an improvement in both storage and collector performance is achieved. There are three advantages:

- In a thermally stratified hot liquid tank, liquid at a higher temperature than the overall mixed mean temperature can be extracted at the top of the tank, thereby improving the satisfaction of the load
- The collection efficiency from the collector is improved since the collector inlet fluid temperature is lower than mixed mean storage temperature
- The stratified storage can be at a lower mixed mean temperature for any given temperature requirement from the load, thereby reducing heat losses from the storage tank

The absolute and relative importance of either of these effects will, of course, depend on the solar system design and the intended application. The thermal stratification described so far is that produced due to buoyancy forces, which ensure highest temperature at the top and lowest temperature at the bottom of the tank (also known as temperature-ordered stratification).

A monotonically increasing temperature from bottom to top is possible in such stratification. However, since complete stratification is never achieved in a real system, an alternative type of stratification employing multiple storage tanks at different temperatures is also meaningful. Such stratification is in fact enforced stratification: the liquid in different tanks remains at different temperatures even when the liquid in each tank is completely mixed, due to the physical separation between tanks.

Forced stratification occurs also in rock beds, since hot air is brought in contact with different parts of the rock bed in the path of its flow and these parts of the rock bed, heated to different temperatures, cannot mix.There are six temperature distribution models to idealize the real temperature distribution in the system.

They are Linear, Stepped, Continuous Linear, General Linear, Basic Three Zone and General Three Zone. Each of above models can be used to idealize the system. But, there is one model, which gives more accurate results. This is the Stepped Temperature Distribution Model. In the governing equations, the stepped-temperature model is used. This model consists of k horizontal zones, each of which is at a constant temperature and can be expressed as:

$$T(h)=\begin{cases} T_1, h_O \le h \le h_1 \\ T_2, h_1 < h \le h_2 \\ \dots\dots. \\ T_K, h_{K-1} < h \le h_K \end{cases} \quad (6)$$

where the heights are constrained as follows:

$$0 = h_0 \le h_1 \le h_2 \le \dots = h_k = H \quad (7)$$

It is convenient to introduce here x_j, the mass fraction for zone j:

$$x_j = m_j/m \quad (8)$$

since, the TES fluid density ρ and the horizontal TES cross-sectional area A are assumed constant here, but the vertical thickness of zone j, $h_j - h_{j-1}$, can vary from zone to zone:

$$m_j = \rho V_j = \rho A(h_j - h_{j-1}) \quad (9)$$

and the total mass is:

$$m = \rho V = \rho AH \quad (10)$$

where, V_j and V denote the volumes of zone j and of the entire TES, respectively. If the last two equations are substituted into the mass fraction formula we get,

$$x_j = h_j - h_{j-1}/H \quad (11)$$

It can be shown that:

$$T_m = \sum_{j=1}^{k} X_j T_j \quad (12)$$

T_m is the fully mixed temperature of the storage or the weighted mean of the zone temperatures, where the weighting factor is the mass fraction of the zone. On the other hand:

$$T_m = \exp\left\{\sum_{j=1}^{k} X_j \ln T_j\right\} = \prod_{j=1}^{k} T_j^{xj} \quad (13)$$

where T_e represents the equivalent temperature of a mixed TES that has the same exergy as the stratified TES. In general, $T_e \ne T_m$, since T_e is dependent on the degree of stratification present in the TES, while T_m is independent of degree of stratification. In fact $T_e = T_m$ is the limit condition reached, when the TES is fully mixed. In the operation of the TES there will be exergy losses and minimization of the exergy losses is desired.

The comparison of these three systems has been given for 10^6 kJ capacities with 40°C temperature difference in Table 4.

Table 4: Comparison of different storage techniques for solar space heating and hot water production applications

Comparison	Sensible heat storage Water	Rock	Latent heat thermal storage material (PCM) (solid-liquid)
A) Different heat storage media			
a) Operating Temp. Range choice	Limited	Large (0-100°C)	Large, depending on the material
b) Specific heat	High	Low	Medium
c) Thermal conductivity properties	Low, convection effects improve the heat transfer rate	Low	Very low, insulating
d) Thermal storage capacity per unit mass and volume for small temp differences	Low	Low	High
e) Stability of thermal cycling	Good	Good	Insufficient data
f) Availability	Overall	Almost overall	Dependent on the choice of the material
g) Cost	Inexpensive	Inexpensive	Expensive
B) Heat transfer properties and life of different types of thermal stores			
a) Required heat exchanger geometry	Simple	Simple	Complex
b) Temperature gradients during charging and discharging	Large	Large	Small
c) Thermal stratification with effect	Existent, works positively	Existent, works positively	Generally non existent
d) Simultaneous charging appropriate discharging exchanger	Possible	Not possible	Possible with selection of heat
e) Integration with solar heating/ cooling systems	Direct integration with water systems	Direct indirect integration with air systems	Indirect integration
f) Cost of pumps,fans,etc.	Low	High	Low
g) Corrosion with conventional materials of construction	Corrosion eliminated through corrosion inhibitors	Non-Corrosive	Presently only limited information available
h) Life	Long	Long	Short

CONCLUSION

It was assumed that containers of phase change system are manufactured using plastics and deformation of the material will begin after 5 years. It was found that the most economical type is the water storage system. On the other hand, water storage system occupies a volume 80 times more than the volume occupied by the phase change system and it has an amortization period, which is four times more than the amortization period of phase change systems. Rock pile systems have larger amortization periods because they have no corrosion and deformation problems, but with their volumes being large, their total initial costs are very high. Phase change systems are the most expensive, but also the most compact types having least using periods because of the material deformation and degradation problems. Because of their compactness, their total initial costs are small. If the problems associated with phase change systems are solved, in the future they are going to be the most promising ones.

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