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STORAGE OF THERMAL ENERGY

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ABSTRACT

This paper is concerned with three modes of thermal energy storage (TES), and these are sensible heat storage (SHS), latent heat storage (LHS), and bond energy storage (BES). The SHS refers to the energy systems that store thermal energy without phase change. The SHS occurs by adding heat to the storage medium and increasing its temperature. Heat is added from a heat source to the liquid or solid storage medium. The thermal stratification is important for the SHS. Heating of a material that undergoes a phase change (usually melting) is called the LHS. The amount of energy stored in the LHS depends upon the mass and latent heat of the material. In the LHS, the storage operates isothermally at the phase change of the material. Lastly, comparison of storage system types is given.

Keywords: Sensible Heat Storage, Latent Heat Storage, Bond Heat Storage, Thermal Stratification, Liquid Storage Media, Economic Aspects of Storage Systems.

I 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 at 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.

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 storage introduced as a by-product of the energy production.

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

$$\eta = \frac{mc(T-T0)}{mc(T\infty-T0)} \qquad \text{------- (1)}$$

Where mc is the total heat capacity of the storage medium and T, T_0 are the maximum and minimum temperatures of the storage during discharging respectively, and $T_{\infty,}$ 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 less than one.

II METHODS OF THERMAL ENERGY STORAGE

There are three basic methods for storing thermal energy:

1. Heating a liquid or a solid, without changing phase: This method is called sensible heat storage. The amount of energy stored depends on the temperature change of the material and can be expressed in the form

$$E = m\int_{T1}^{T2} CpdT \qquad \text{-------- (2)}$$

where m is the mass and C_p; the specific heat at constant pressure. T_1 and T_2 represent the lower and upper temperature levels between which the storage operates. The difference $(T_2 - T_1)$ is referred to as the temperature swing.

2. Heating a material, which undergoes a phase change (usually melting): This is called latent heat storage. The amount of energy stored (E) in this case depends upon the mass (m) and latent heat of fusion (λ) of the material. Thus,

$$E = m\lambda \qquad \text{---------------- (3)}$$

The storage operates isothermally at the melting point of the material. If isothermal operation at the phase change temperature is difficult, the system operates over a range of temperatures T_1 to T_2 that includes the melting point. The sensible heat contributions have to be considered and the amount of energy stored is given by

$$E = m\left[\left\{\int_{T1}^{T*} CpsdT\right\} + \lambda + \left\{\int_{T*}^{T2} CpldT\right\}\right] \qquad \text{-------------------- (4)}$$

Where C_{ps} and C_{pl} represents the specific heats of the solid and liquid phases and T^* is the melting point.

3. Using heat to produce a certain physicochemical reaction and then storing the products. Absorbing and adsorbing are two examples for the bond reaction. The heat is released when the reverse reaction is made to occur. In this case also, the storage operates essentially isothermally during the reactions. However, the temperature at which heat

flows from the heat supply is usually different, because of the required storage material and vice versa. Of the above methods, sensible and latent heat storage systems are in use, while bond energy storage systems are being proposed for use in the future for medium and high temperature 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 two or three 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 Equation (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 one year. For a well-designed short-term storage unit, the value of the efficiency should generally exceed 80 percent.

Table 1 gives an overview of thermal energy storage methods

Type of thermal energy storage	Functional principal	Phases	Examples
Sensible Heat	Temperature change of the medium with highest possible heat capacity.	Liquid	Hot water, organic liquids, molten salts, liquid metals.
		Solid	Metals, minerals, ceramics.
Latent Heat	Essentially heat of phase change.	Liquid - Solid	Nitrids, chlorides, hydroxides, carbonates, flourides, entectics.

		Solid - Solid	Hydroxide
Bond Energy	Large amount of chemical energy is absorbed and released due to shifting of equilibrium by changing pressure and temperature.	Solid – Gas	CaO / H_2O, MgO / H_2O, $FeCL_2 / NH_3$
		Gas– Gas	CH_4 / H_2O
		Liquid – Gas	L_iB_r / H_2O, N_aOH / H_2O, H_2SO_4 / H_2O

Table 1: Overview of Thermal Energy Storage Methods

III SENSIBLE HEAT STORAGE

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

$$Qs = mc\Delta T = V\rho c\Delta T \qquad \text{------------------ (5)}$$

Where m is mass, V is volume, c is specific heat, ρ is density and $\Delta T = T_{max} - T_{min}$ 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

$$V = Qs / \rho c(1 - \varepsilon)\Delta T \qquad \text{--------------------- (6)}$$

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

$$V = Qs / m = c\,(T_{max} - T_{min}) \qquad \text{----------------} \ (7)$$

and

$$q_v = Qs / V = \rho c\,(T_{max} - T_{min}) \qquad \text{----------------}(8)$$

IV 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 to 100 liters of storage per square meter of collector area. Further details about the storage of solar energy are given in Section 3.3. 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 to 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 shown in Figure 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.

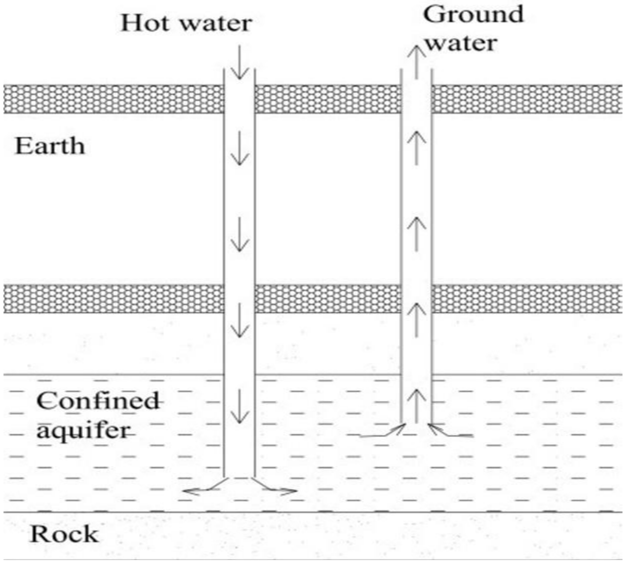

Figure 1: Underground sensible energy storage system.

Heat transfer oils are used in sensible heat storage systems for intermediate temperatures ranging from 100 to 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 percent $NaNO_2$, 7 percent $NaNO_3$ and 53 percent 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:

1. Water is inexpensive, easy to handle, non-toxic, non-combustible and widely available.
2. Water has a comparatively high specific heat and high density
3. Heat exchangers may be avoided if water is used as the heat carrier in the collector.

4. Natural convection flows can be utilized when pumping energy is scarce.
5. Simultaneous charging and discharging of the storage tank is possible.
6. Adjustment and control of a water system is variable and flexible.

Disadvantages:

1. Water might freeze or boil
2. Water is highly corrosive
3. Working temperatures are limited to less than 100°C and often have to be far below this boiling temperature.
4. 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 below. 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.

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	- do -	Up to 97	800	2500	-
Butanol	- do -	Up to 118	809	2400	-
Isobuthanol	- do -	Up to 100	808	3000	-
Isopentanol	- do -	Up to 148	831	2200	-
Octane	- do -	Up to 126	704	2400	-

Table 2: Properties of Liquid Media for Sensible Heat Storage.

V 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 to100°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 to 5 cm. An approximate rule of thumb for sizing is to use 300 to 500 kg of rock per square meter of collector area for space heating applications. Rock or pebble-bed storages 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 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:

1. Rocks are not toxic and non-flammable
2. Rocks are inexpensive
3. Rocks act both as heat transfer surface and storage medium
4. 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. 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 listed at Table 3

Medium	Density (kg/m^3)	Specific Heat (J/kg.K)	Heat Capacity $\rho c x 10^{-6}$ ($J/m^3.K$)	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

Table 3: Solid Media Properties for Sensible Heat Storage

VI 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 Figure 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.

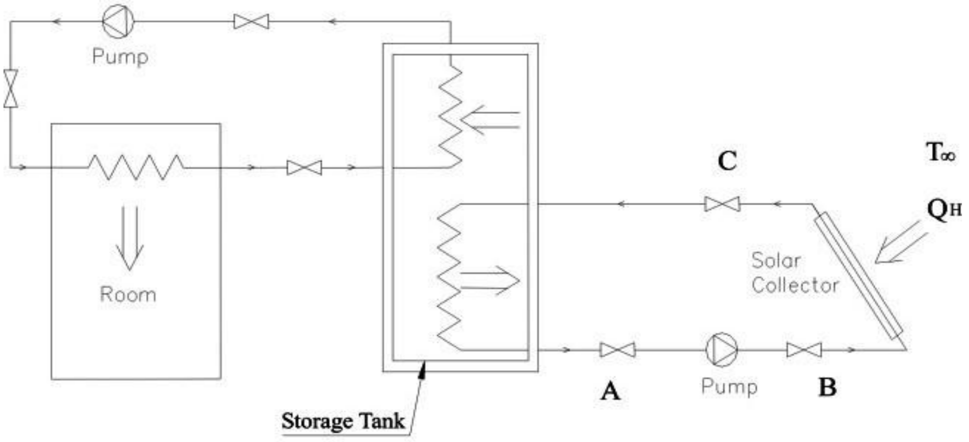

Figure 2: Schematic Diagram of the Solar Energy Storage System.

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 Q_H 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, B, C are closed. After the storage period D, E, F is 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.

VII 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 isolation 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 illustrated in Figure 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.

2. The collection efficiency from the collector is improved since the collector inlet fluid temperature is lower than mixed mean storage temperature.

3. 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.

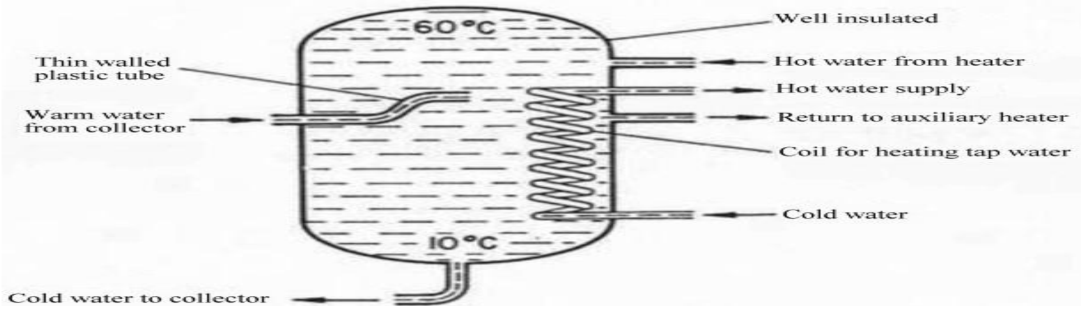

Figure 3: Thermally stratified hot liquid tank.

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

$$T(h) = \left\{ \begin{matrix} T1, h0 \ \leq h \leq h1 \\ T2, h < h \leq h2 \\ \dots \dots. \\ Tk, hk-1 < h < hk \end{matrix} \right\} \text{-------------------------} \ (09)$$

Where the heights are constrained as follows:

$$0 = ho \leq h1 \leq h2 \leq \ldots\ldots\ldots\ldots.. \leq hk = H \ \text{-------------------} \ (10)$$

It is convenient to introduce $x_{j,}$ the mass fraction for zone j:

$$X_i = \frac{mi}{m} \qquad \text{----------------} \ (11)$$

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,

$$m_j = \rho \ Vj = \rho \ A\ (h_j - h_{j-1}) \qquad \text{-------------------} \ (12)$$

and the total mass is

$$m = P\text{v} = P\text{ah} \qquad \text{--------------------} \ (13)$$

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:

$$x_j = \frac{hj - hj-1}{H} \quad \text{----------------------}(14)$$

It can be shown that:

$$Tm = \sum_{j-1}^{k} xjTj \quad \text{---------------------------}\ (15)$$

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:

$$Te = \exp\left[\sum_{j-1}^{k} xj\ in\ Tj\right] = \prod_{j-1}^{k} Tjxj \quad \text{---------------}\ (16)$$

where T_e represents the equivalent temperature of a mixed TES that has the same exergy as the stratified TES. In general, $T_e \neq T_m$, 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.

PHASE CHANGE ENERGY STORAGE

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 vapor as latent heat of vaporization. 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 one kilogram of ice is 80 times more than that required to raise the temperature of one kilogram of water one degree Celsius.

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:

1. High energy density or high volumetric energy capacity is desired, e.g., in habitat where space is at a premium, or in transportation where both volume or weight must be kept to a minimum
2. The load is such that energy is required at a constant temperature or within a small range of temperatures, or
3. 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 storages of small capacities.

BOND HEAT STORAGE

Energy may be stored in systems composed of one or more chemical compounds that absorb or release energy through bond reactions. There are many forms in which energy can be stored through bond reactions. Bond storage involves an endothermic reversible reaction, which can be reversed when required to release heat. The chemical produced can often be stored cold (without losses) and can often be transported easily. For storage of thermal energy in bond energy, one prefers reversible chemical reactions. During charging the supplied heat For a bond reaction to be considered for energy storage, the following conditions should be met:

- The reaction should be run near equilibrium, i.e. reversible.
- The reactant, with or without addition of a photo sensitizer, should be able to use as much of the solar spectrum in the terrestrial atmosphere as possible.
- The energy stored in the bond energy should be large enough.
- The reactants should be cheap.

An important factor to be considered in bond process is the recovery of the reagents or the intermediary chemicals. It is estimated that in each chemical cycle, recovery yields of 99.9 or even 99.99 % have to be achieved if the bond process are to be viable.

HIGH TEMPERATURE THERMAL ENERGY STORAGE

High temperature TES is important in solar power plants and in utilization of waste heat in the industrial processes. At high temperatures the selection of a proper storage medium is a rather complex problem. The development and design of high temperature thermal energy storage systems have some difficulties, because they operate at about 900 ^oC and require a very small temperature fluctuation. In addition, the system has size restrictions and a low flow fluid pressure drop. At high temperatures the safety aspects of thermal energy storage are important considering corrosion of the container. High-pressure helium or oils are usually used for high temperature storage in solids. The heat transfer fluids must be compatible with the solids. The candidate fluids must have low vapor pressure, high specific heat and low cost. The magnesia may be used as the material for the storage medium effectively. Molten-salt mixtures containing sodium nitrite and sodium and potassium nitrates can be used to store heat up to about 540 ^oC.

COLD STORAGE

The thermal energy can also be stored at temperatures lower than environment and it is called cold storage. The basic motivation to use a cold storage system is its potential to save operating cost. By adding cold storage it is possible to use the cheapest electricity rate during off peak periods offered by the companies. The investment is made on the cold storage system only with the prospect of saving money. However when cold storage systems save operating cost, they cost more in capital investment than a conventional air conditioning system without cold storage. There are three basic control strategies for cold storage systems: Chiller priority control, storage priority control and optimal control

COMPARISON OF STORAGE SYSTEM TYPES INCLUDING ECONOMIC ASPECTS

Various types of energy storage techniques are compared in Table 4. The main problem with water storage systems is the corrosion for long operation periods. Another disadvantage of water storage systems is that volume of the storage may be very large for large heat capacities and therefore the whole system becomes very heavy. With large storage units, there is also stratification problem and because of 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 loses its energy storage characteristics after a period of time.

The comparison of these three systems has been given for 10^6 kJ capacities with 40°C temperature difference. It was assumed that containers of phase change system are manufactured using plastics and deformation of the material will begin after five 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.

On weight and volume basis, bond storage has a greater capacity than other systems. High pressure (50 atm) CO/H_2 mixtures, for example, have a storage capacity of an order of magnitude higher than liquid water (though less than salt hydrates and much less than metal hydrides). Although adequate thermodynamic data exist for most of the bond reactions of interest, the bond kinetics data are very scarce even for simple system like methane / water.

		Sensible Heat Storage		Latent Heat Thermal Storage Material (PCM) (solid – liquid)
		Water	Rock	
A). Comparison between different heat storage media				
1	Operating temp, range choice	Limited(0 - 100^0)	Large	Large, depending on the of the material
2	Specific heat	High	Low	Medium
3	Thermal conductivity properties	Low, convection effects improve the heat transfer rate	Low	Very Low, insulating
4	Thermal storage per unit mass and volume for small temp differences	Low	Low	High
5	Stability to thermal cycling	Good	Good	Insufficient data
6	Availability	Overall	Almost Overall	Dependent on the choice of material
7	Cost	Inexpensive	Inexpensive	Expensive
B) Comparison of heat transfer properties and life of different types of thermal stores				
1	Required heat exchanger	Simple	Simple	Complex

	geometry			
2	Temperature gradients during charging and discharging	Large	Large	Small
3	Thermal stratification t with effect	Existent, works	Existent, works	Generally non-existent
		Positively	Positively	Proper choice of material
4	Simultaneous charging appropriate discharging exchanger	Possible	Not possible	Possible with selection of heat
5	Integration with solar heating / cooling systems	Direct integration with water systems	Direct integration with air systems	Indirect integration
6	Cost of pumps, fans, etc	low	High	low
7	Corrosion with conventional materials of construction	Corrosion eliminated through corrosion information	Non-Corrosive	Presently only limited information available
8	Life	Long	Long	Short

Table 4: comparison of different techniques for solar space heating and hot water production application

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