full-size car. They must be mated to a faster energy storage device, and for this, coupling with ultra-capacitors is superior in many respects to batteries.

3.2.5 Thermal Energy Storage

(a) Sensible Heat Storage

In this type of storage, thermal energy is stored by virtue of heat capacity and the change in temperature of the material during the process of charging and discharging. The temperature of the storage material rises when energy is absorbed and drops when energy is withdrawn. The charging and discharging operations, in a sensible heat-storage system, can be expected to be completely reversible for an unlimited number of cycles over the lifespan. On the basis of heat-storage media, it can be classified as (i) liquid media storage, (ii) solid media storage, and (iii) dual media storage.

(i) Liquid Media Storage Of available liquids, water can be considered to be the most suitable liquid media for storage below 100°C. Water has the following advantages:

1. It is abundant and inexpensive.
2. It is easy to handle, non-toxic and non-combustible.
3. Its flow can take place by thermo-siphon action.
4. It has high density, high specific heat, good thermal conductivity and low viscosity.
5. Can be used both as storage medium as well as working medium (thus eliminating the need for a heat exchanger, e.g., in a space-heating system)
6. Charging and discharging of heat can occur simultaneously.
7. Control of water system is flexible.

The main disadvantages with water as storage media are

1. Limited temperature range (0°C to 100°C).
2. Corrosive medium
3. Low surface tension (i.e., leaks easily)

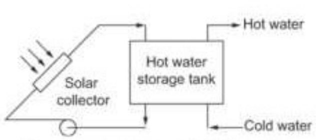

Fig. 3.6 *Short-term thermal energy storage in water*

A short-term thermal energy storage system is shown in Fig. 3.6, where hot water is stored in a well-insulated tank. Storage in this manner is economical only for a few days since the heat losses become prohibitive over long durations.

Though water is the best choice as a heat-storage medium in a space-heat system; other liquids such as oils, liquid metals and molten salts have also been used in solar thermal power plants. Table 3.2 shows the thermophysical properties of selected liquids for sensible heat

storage. Out of these, water appears to be the best sensible storage liquid available because it is inexpensive and has high specific heat. However, above 100°C, the storage tank must be able to contain water at its vapour pressure, and therefore, the storage-tank cost rises sharply. Organic oils, molten salts and liquid metals circumvent this problem.

Table 3.2 *Thermophysical properties of selected liquids for sensible heat storage*

S.N.	Medium	Temp. range (°C)	Density (kg/m³)	Heat capacity (J/kg °K)
1.	Water	0 to 100	1000	4190
2.	Thermional 66	–9 to 343	750	2100
3.	Hitec (molten salt)	142 to 540	1680	1560
4.	Engine oil	Up to 160	888	1880
5.	Lithium	180 to 1300	510	4190
6.	Sodium	100 to 760	960	1300
7.	Octane (organic liquid)	Up to 126	704	2400

Large size and long-term storage of hot water in underground reservoirs is possible without the use of special insulating materials. Figure 3.7 shows one such system schematically. Here, cold ground water from Zone A of an aquifer is heated by passing it through a heat exchanger and returned to Zone B where it is stored. In the discharge mode, the hot water from Zone B flows back through the heat exchanger where it gives out the stored heat and returns to Zone A. The heat from such aquifers can be retrieved with negligible losses, which may be of the order of one per cent only.

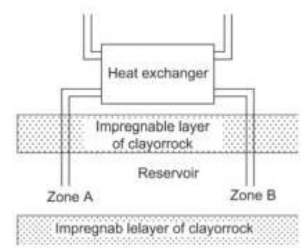

Fig. 3.7 *Long-term thermal storage in underground layers*

(ii) Solid Media Storage (Packed Bed Storage) It utilizes the heat capacity of a bed of loosely packed solid materials such as rocks, metals, concrete, sand, bricks, etc., to store energy. A fluid, usually air, is circulated through the bed to add or remove energy. Here, energy can be used at low or high temperature since these will neither freeze nor boil. The energy change for 50°C is about 10 Wh/kg for most rocks, concrete and iron ore.

A packed-bed storage unit consists of a container, a screen to support the bed, support for the screen and inlet and outlet ducts. Flow is maintained through the bed in one direction, during addition of heat and in the opposite direction during removal of heat. A typical packed-bed storage is shown in Fig. 3.8.

The main advantages and disadvantages of such a system are the following

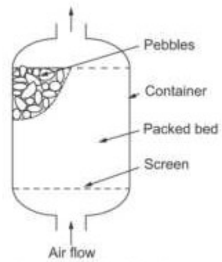

Fig. 3.8 *Packed-bed storage unit*

Advantages

- Rocks are abundant, low cost, easy to handle, non-toxic and non-combustible
- High storage temperatures are possible
- Heat exchanger can be avoided
- No freezing problem
- No corrosion problem

Disadvantages

- Storage volumes are large
- High pressure drop
- Simultaneous charging and discharging are not possible

(iii) Dual Media Storage In dual media storage, both solid and liquid sensible heat storage materials are used. These solid and liquid materials may be combined in a number of ways. One of them is to jointly use the bedrock and water tank—a hybrid system, with water tank surrounded by bedrock.

(b) Latent Heat Storage (Storage in Phase Change Materials)

In this class of storage, energy is stored by virtue of latent heat of change of phase of the storage medium. Phase change materials have considerably higher thermal energy storage densities as compared to sensible heat storage materials and are able to absorb or release large quantities of energy at a constant temperature. Therefore, these systems are more compact but more expensive than sensible heat-storage systems. Various phase changes that can occur are

- solid–solid (lattice change)
- solid–gas
- solid–liquid
- liquid–gas

Solid–gas and liquid–gas transformations are not employed in spite of large latent heats as large changes in volume make the system complex and impracticable. In solid–solid transition, heat is stored as the material is transformed from one crystalline form to another. These transitions involve small volume changes, however, most of them have small latent heats.

The solid–liquid transformations include storage in salt hydrates. Certain inorganic salts, which are soluble in water and form crystalline salt hydrates, are employed. Let an inorganic salt, which is soluble in water be represented by

$X(Y)_n$. The crystalline salt hydrate is symbolized by $X(Y)_n \cdot mH_2O$. On heating up to the transition temperature, the hydrate crystals release water of crystallization and the solid remainder (anhydrous salt) dissolves in the released water as the following reaction takes place:

$$\underset{\text{(Solid)}}{X(Y)_n \cdot mH_2O} + \Delta H \leftrightarrow \underset{\text{(Liquid: aqueous solution of anhydrous salt)}}{X(Y)_n + mH_2O}$$

One problem with most salt hydrates is that the released water of crystallization is not sufficient to dissolve all the solid phase present. Due to density difference, the anhydrous salt settles down at the bottom of the container. This incongruent melting makes the process irreversible since the anhydrous salt at the bottom is unable to find water for recrystallization to the original hydrate. The recrystallization of an incongruently melting salt can be achieved either by (i) the use of suspension media or thickening agent or by (ii) mechanical means (vibration, stirring, etc.)

The heat transfer properties of some phase change materials are given in Table 3.3.

Table 3.3 *Heat-transfer properties of phase-change storage materials*

S N	*Material*	*Chemical compound*	*Melting point (°C)*	*Heat of fusion (kJ/kg)*	*Density kg/m³*
1.	Sodium sulphate decahydrate (Glauber's salt)	$Na_2SO_4 \cdot 10H_2O$	31-32	251	1534
2.	Sodium thiosulphate	$Na_2S_2O_3 \cdot 5H_2O$	48-49	209	1666
3.	Calcium chloride hexahydrate	$CaCl_2 \cdot 6H_2O$	29-39	177	1634
4.	Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	32-36	247	1442
5.	Disodium phosphate decahydrate	$Na_2HPO_4 \cdot 12H_2O$	36	265	1522

Other potential phase change materials apart from salt hydrates are paraffins (e.g., $C_{18}H_{38}$ etc., alkanes containing 14 to 40 C-atoms) and non-paraffin organic materials (e.g., esters, fatty acids, alcohols and glycols), which are suitable at certain situations.

3.2.6 Biological Storage

Solar energy can be stored biologically in plants by fixing carbon from CO_2 available in the atmosphere. The fixation of carbon atoms from atmospheric CO_2 to carbohydrates proceeds by a series of stages in green plants. This process