EN 671 Solar Energy Conversion Technology

Thermal Energy Storage

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- ✓ Sensible heat storage
- ✓ Latent heat storage
- ✓ Thermochemical storage

Need of Energy Storage

- ✓To supply energy reliably, efficiently, economically.
- ✓ To meet the peak demand.
- ✓ To offset the adverse effect of fluctuating demand of electricity.
- ✓To assure a steady output from power plants.
- ✓To supply energy at demand period for intermittent generation technologies like wind and solar energy where production varies with demand.
- ✓To provide renewables with a zero GHG emission backup.

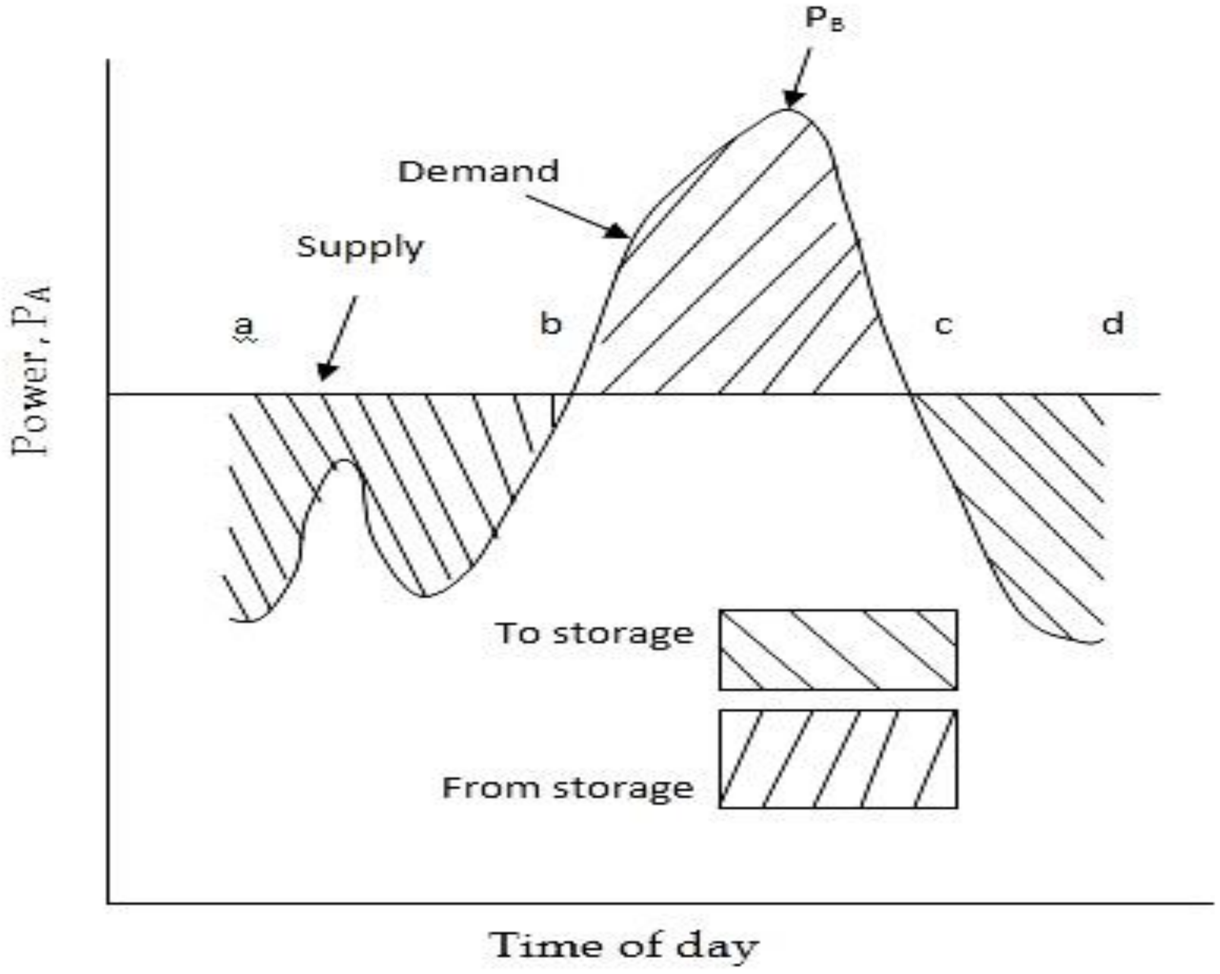
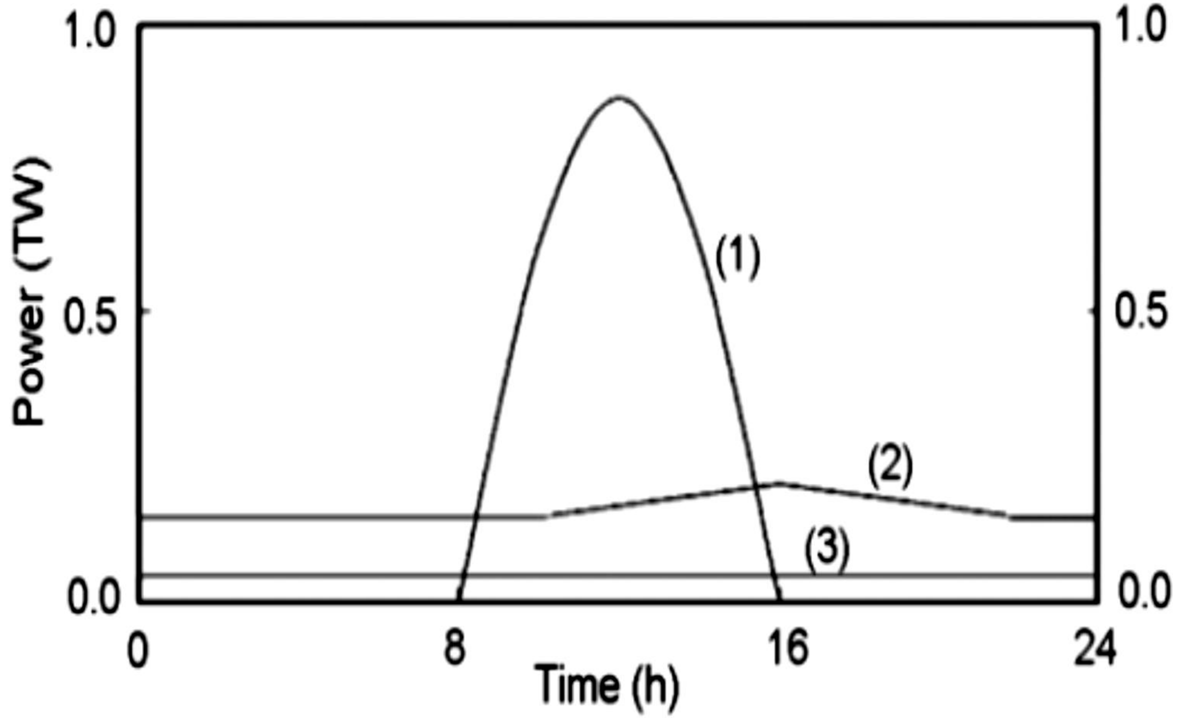


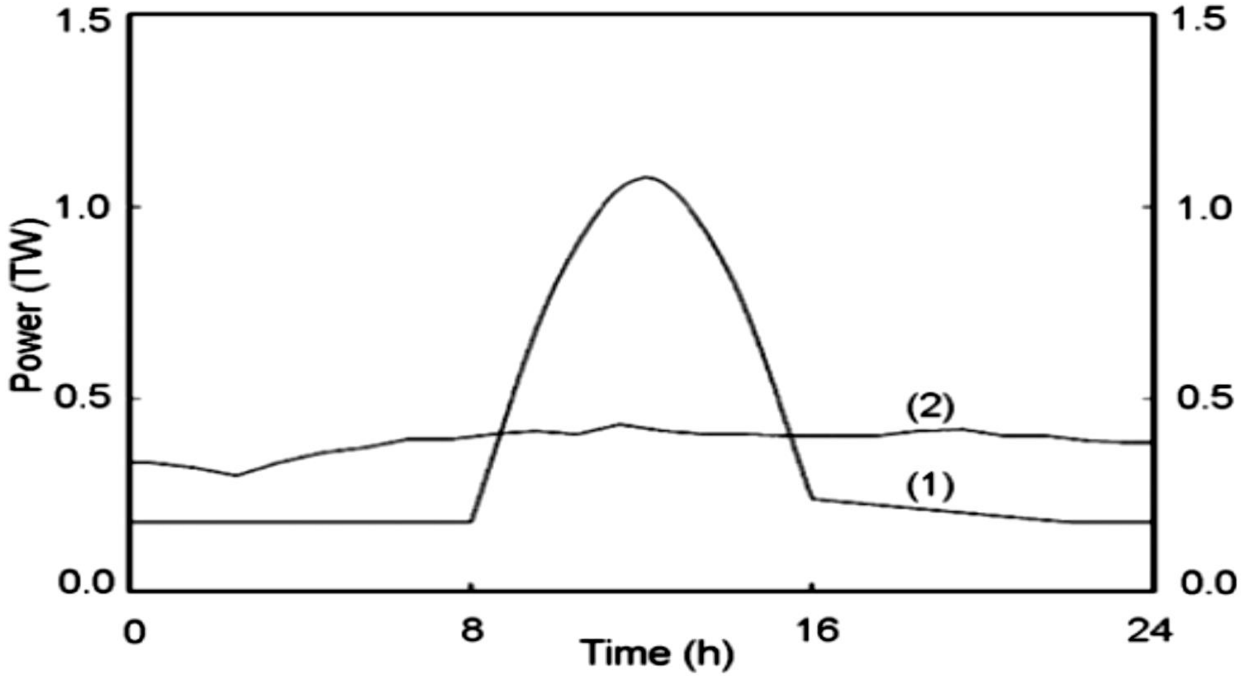
Fig. Power supply and demand curve for a day

Diurnal variation of power production



Curve 1: Solar power, curve 2: wind power, curve 3: hydroelectric power and other miscellaneous sources

Fig. Diurnal variation of power produced by renewable sources over a typical sunny day



Curve 1: Production, Curve 2: demand

Fig. Comparison of diurnal variation over a typical sunny day

Important factors and schemes for energy storage systems

- Thermal Energy Storage
- Electrochemical Energy Storage
- Pumped Hydro
- Compressed air Energy storage
- Energy storage by flywheels
- Magnetic Energy Storage
- Chemical Energy Storage
- Hydrogen storage

- Temperature range of application
- Energy Density
- Minimum heat loss
- Cost
- Efficiency
- Environmental impact

Thermal Energy Storage

What is the need???

The intermittent, variable and unpredictable nature of solar radiation generally leads to a mismatch between the rate and the time of collection of solar energy and the load needs of a thermal application.

It is often required to put energy storage system in between.

How it works???

The storage system stores energy when the collected amount is in excess of the requirement of the application and discharges energy when the collected amount is inadequate.

What is the size???

The size of a storage system is largely determined by the specific purpose for which it is used.

Various situations for using a thermal energy storage

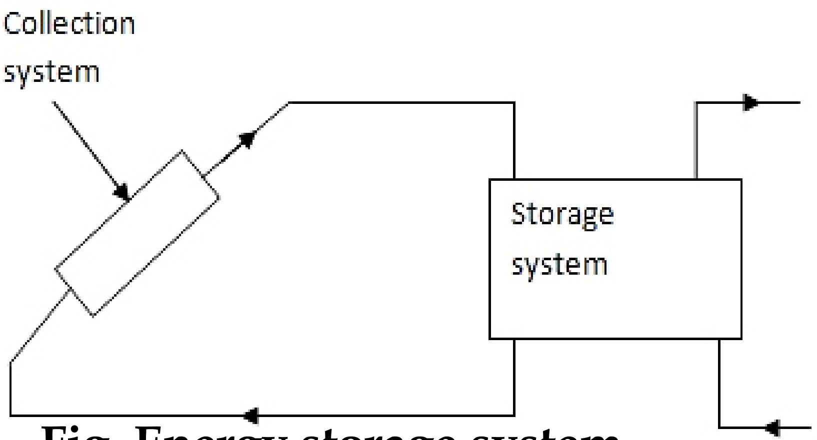


Fig. Energy storage system

Buffer Storage: Energy requirement is essentially the same as the collection; store energy for short intervals of time and small in size.

Diurnal storage: load demand is 24 hours, whereas collection takes place only during the sunshine hours. A system larger than a buffer storage having the capacity to store energy for a day or two is required.

Annual Storage : storage system stores energy during the summer when the collection is in excess of the demand, and delivers the excess energy in winter when the collection is less than the demand. A large long-term storage system is required.

1 Energy collected, 2 Load requirement

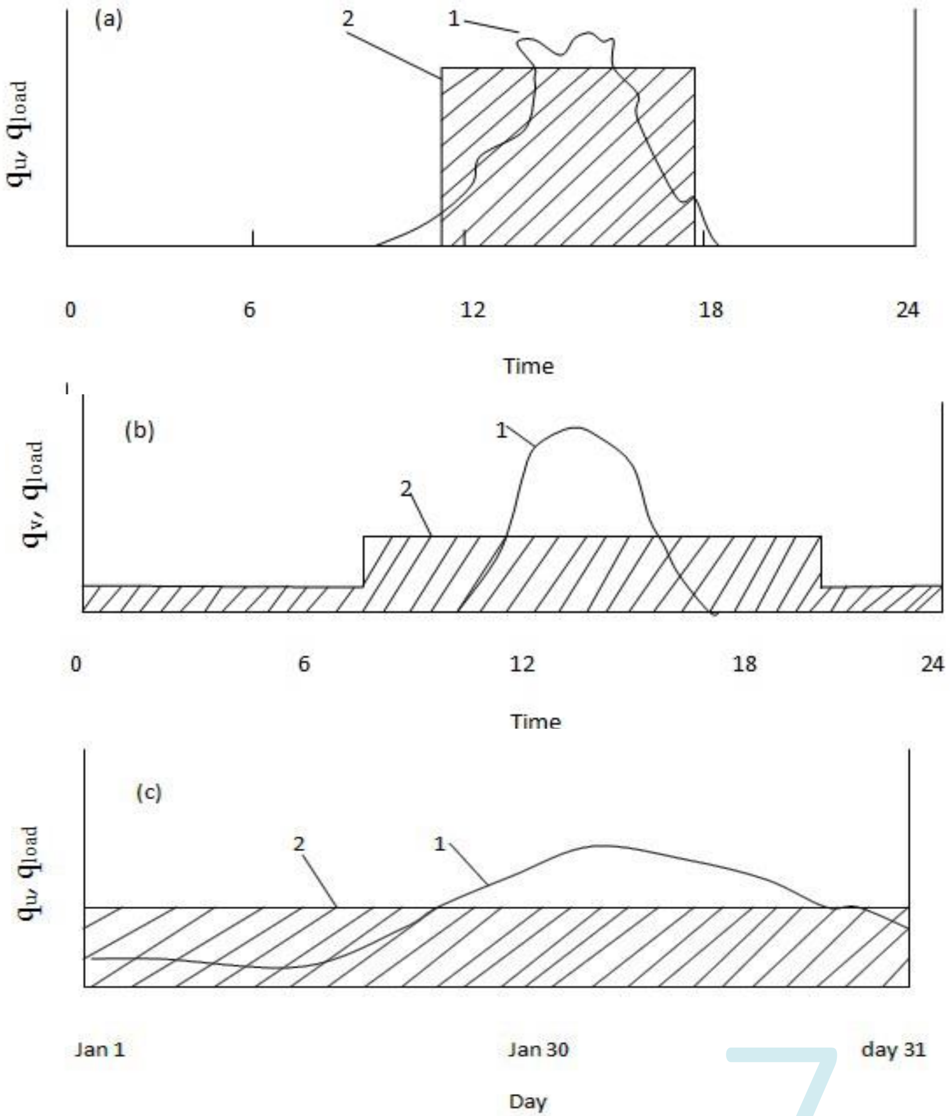


Fig. Different situation of storing thermal energy

Basic methods for storing thermal energy

- **Sensible heat storage (heating a liquid or a solid which does not change phase): The amount of energy stored is dependent on the temperature change of the material.**

T_1-T_2= temperature swing

$$\boxed{E = m\int_{T_1}^{T_2} C_p dt} \qquad \text{(a)}$$

- **Latent heat storage (heating a liquid or a solid which undergoes a phase change): The amount of energy stored is depends upon the mass and the latent heat of fusion of the material.**
  - ✓ **Storage operates isothermally at melting point of the material.**

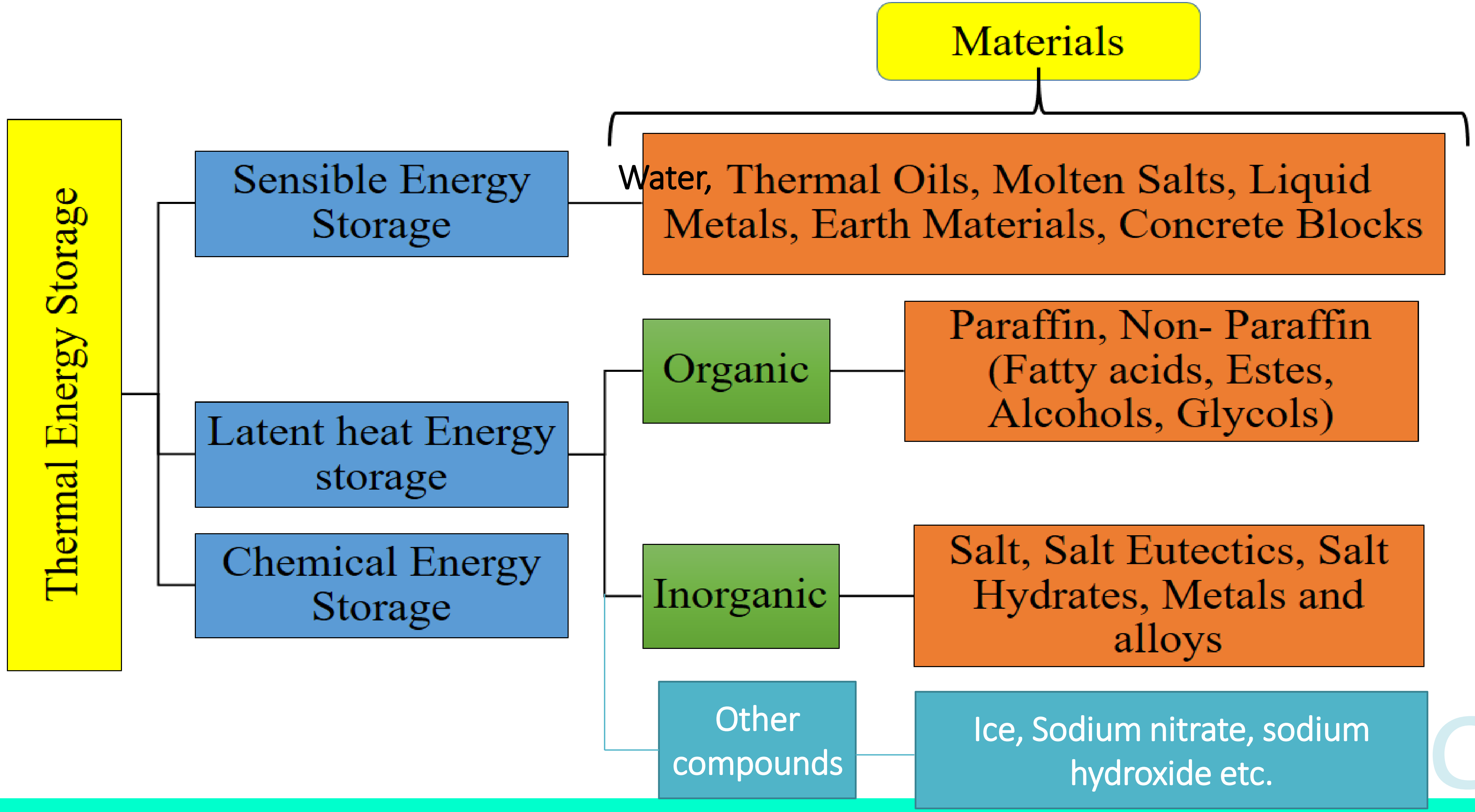
$$\boxed{E = mL} \qquad \text{(b)}$$

  - ✓ **If isothermal operation at the phase change temperature is difficult, the system operates over a range of temperatures which includes melting point.**

$$\boxed{E = m\left[\left\{\int_{T_1}^{T^+} C_{ps} dT\right\} + L + \left\{\int_{T^+}^{T_2} C_{pl} dT\right\}\right]} \qquad \text{(c)}$$

- **Thermochemical storage: Using heat to induce a certain chemical reaction and then storing the product, the heat is released when the reverse reaction is made to occur.**

Different methods and materials for Thermal Energy Storage



Design considerations

- The temperature range over which the storage has to operate.
- The capacity of the storage has a significant effect on the collectors. A smaller storage unit operate at a higher mean temperature. This results in a reduced collector output as compares to a system having a larger storage unit.
- Heat losses from the storage have to be kept a minimum.
- Cost of the storage unit (includes cost of storage medium, the containers, insulation and operating cost).

Storage capacity of solar thermal storage systems

Availability of solar radiation

Nature of thermal process

Economic assessment of solar vs. auxiliary energy

Physical and chemical properties of the storage medium employed

Sensible heat storage

Simple in design than latent heat or thermochemical systems

Sensible heat storage systems

Suffer from the disadvantage of being bigger in size

Cannot storage or deliver energy at a constant temperature

Various substances used:

- water
- Heat transfer oil
- Inorganic molten salts
- Rock, pebbles and refractories

✓ Water being used for temperature below 100°C

✓ Refractory bricks being used for temperature around 1000 °C

✓ An important criterion is selecting a material for sensible heat storage is its ρC_p value.

✓ 75 – 100 liters of storage per square meter of collector area.

Sensible heat storage media

The choice of storage media depends on the nature of solar thermal process

- ❑Water storage
- ❑Air based thermal storage (packed bed storage)
- ❑Storage walls and floors
- ❑Buried earth thermal storage

❑**Water has three times more heat capacity than rock on a volume basis, it means rock requires three times more volume than water to store the same amount of sensible heat.**

Table : Properties of sensible heat storage materials

Materials	Specific heat kJ/ kg. K	Density kg/ m^3	Volumetric specific heat kJ/ m^3. K
Adobe	1.0	1700	1700
Aluminum	0.896	2700	2420
Brick	0.84	1920	1600
Concrete	0.92	2240	2100
Fiberglass Batt insulation	0.71-0.96	5-30	4-30
Polyurethane Board insulation	1.6	24	38
Rock pebbles	**0.88**	**1600**	**1410**
Steel	0.48	7850	3800
Stone(granite)	0.88	2720	2400
Water	**4.18**	**1000**	**4180**
Wood	2.5	510	1300

Water Storage

The use of water is particularly convenient. Water is used as

- ❑The mass and heat transfer medium in the solar collector

Water is the ideal material to store useable heat because:

- ❑It is low in cost
- ❑It has a high specific heat

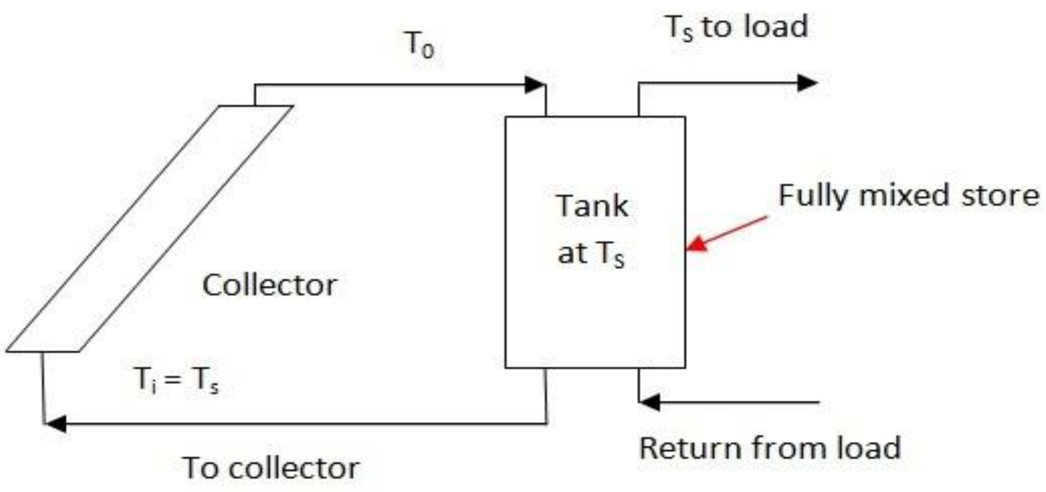


Fig. Solar space heating

❑A solar space heating system can also use water as the storage as well as the transport medium.

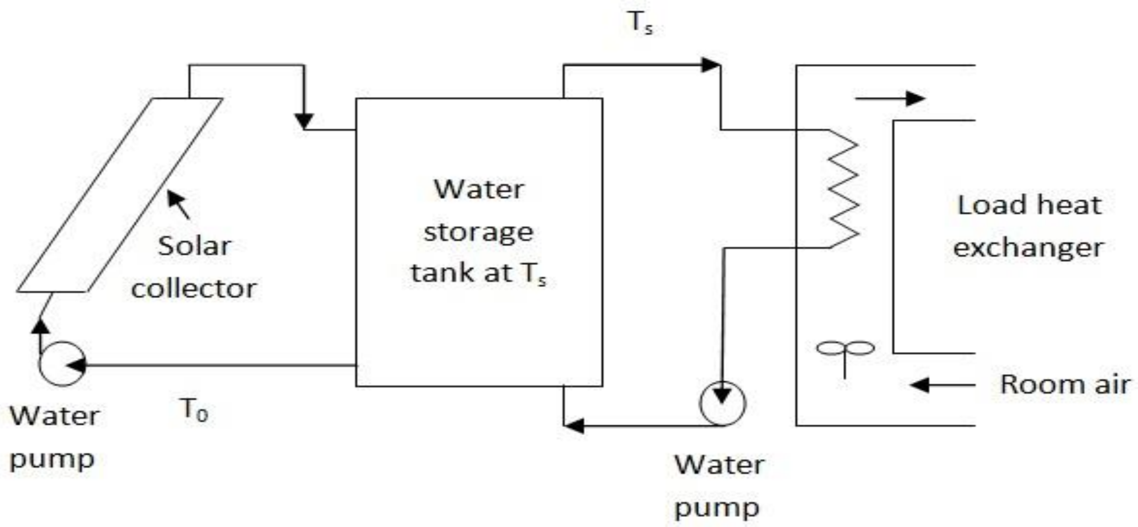


Fig. Solar space heating with water storage tank

Storage in solids

- ✓ Approximate thumb rule followed for sizing : 300 to 500 kg rock per square meter of collector area for space heating.

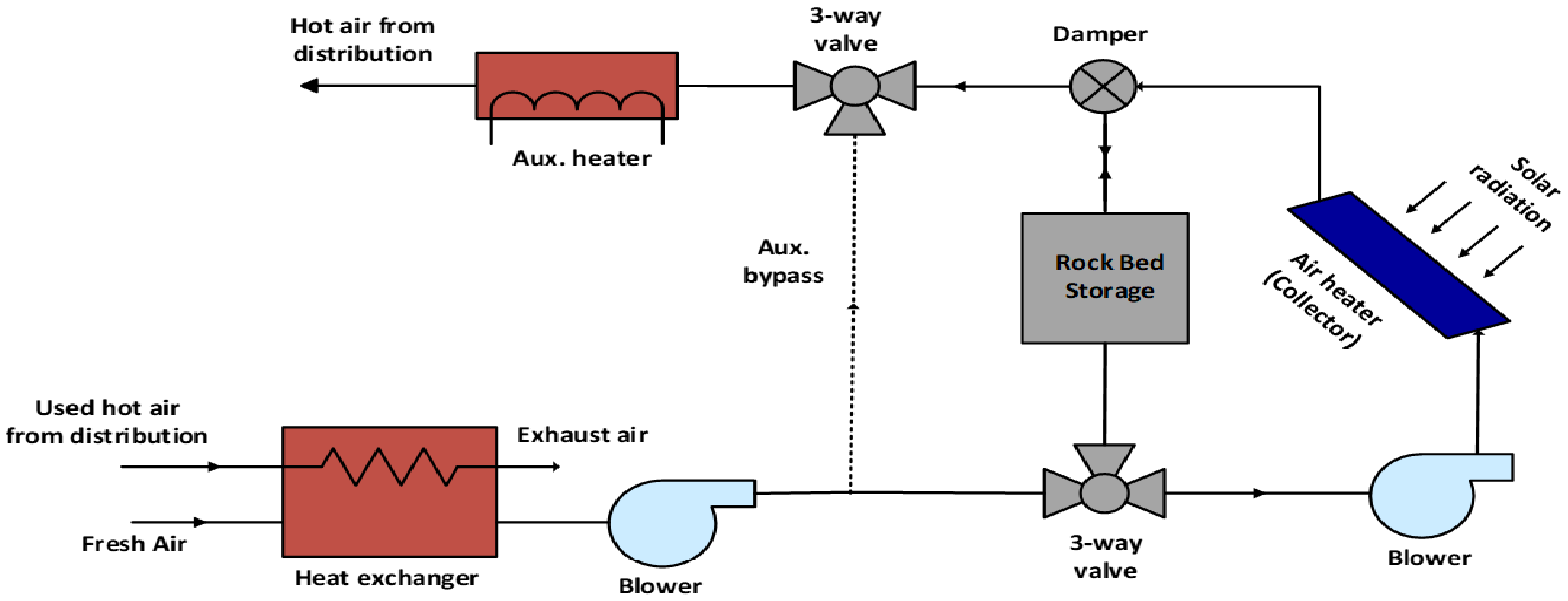


Fig. Application of solid as sensible heat storage medium

Sensible heat storage (problem)

Example 1: Calculate the energy required to heat 270 litres of water from 15°C to 55°C. Assume that no heat loss is taking place from the tank where water is kept.

We have the data:

- **The density of water is 993, C_P= 4.18**
- **The price of electricity is Rs. 6/kWh**
- **1 Joule is equal to a watt second**
- **ΔT=40 °C**

Q = 270 * 993kg/cum * 4.18 kJ/ kg ° C * 40°C
= 44,827.99 kJ (or 44.8 MJ)
= 44,827.99 kWs
= 12.45 kWh

At an electrical energy cost of Rs. 6/ kWh, this energy costs:
= Rs. 6/ kWh * 12.45 kWh
= Rs. 74.7

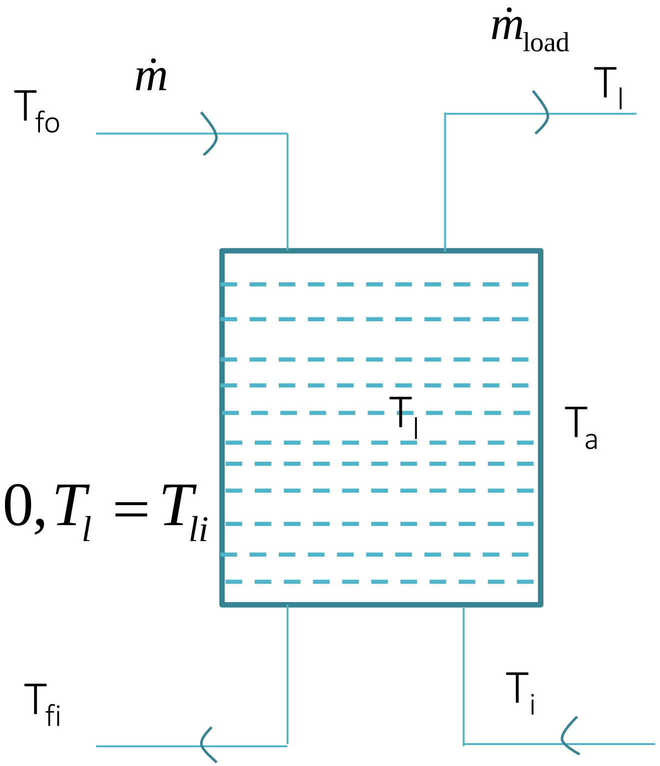
Analysis of a liquid storage tank: well mixed situation

An energy balance on the tank yields:

$$\boxed{\left[\left(\rho VC_p\right)_l+\left(\rho VC_p\right)_t\right]\frac{dT_l}{dt}=q_u-q_{load}-(UA)_t\left(T_l-T_a\right)}$$

$$\boxed{\left(\rho VC_p\right)_l+\left(\rho VC_p\right)_t=\left(\rho VC_p\right)_e}$$

$$\boxed{\left(\rho VC_p\right)_e\frac{dT_l}{dt}=q_u-q_{load}-(UA)_t\left(T_l-T_a\right)}$$



Well-mixed sensible heat liquid storage tank

Assuming that q_u, q_{load}, T_a are constant subject to the initial condition $t=0, T_l=T_{li}$

$$\left(\rho VC_p\right)_e\frac{dT_l}{dt}-\left[q_u-q_{load}-(UA)_t\left(T_l-T_a\right)\right]=0$$

Let

$$\theta_l(t)=q_u-q_{load}-(UA)_t\left(T_l-T_a\right) \qquad t=0, \theta_l(t)=\theta_{li}$$

$$\frac{d\theta_l(t)}{dt}=-(UA)_t\frac{dT_l}{dt}\Rightarrow\frac{dT_l}{dt}=-\frac{1}{(UA)_t}\frac{d\theta_l(t)}{dt}$$

Analysis of a liquid storage tank (contd.)

$$\left(\rho V C_p\right)_e \frac{dT_l}{dt} - \left[q_u - q_{load} - (UA)_t \left(T_l - T_a\right)\right] = 0$$

$$-\frac{1}{UA}\frac{d\theta(t)_l}{dt} - \frac{1}{\left(\rho C_p V\right)_e}\theta(t) = 0$$

$$\Rightarrow \frac{d\theta(t)}{dt} + \frac{UA}{\left(\rho C_p V\right)_e}\theta(t) = 0$$

ODE, its general solution is, $\theta(t) = C \times \exp^{-\frac{UA}{\rho C_p V}t}$ $\quad t = 0, \theta_l(t) = \theta_{li}$

$$\boxed{\begin{aligned} &\Rightarrow \frac{\theta(t)}{\theta_{li}} = e^{-\frac{UA}{\rho C_p V}t} \\ &\Rightarrow \frac{q_u - q_{load} - (UA)_t\left(T_l - T_a\right)}{q_u - q_{load} - (UA)_t\left(T_{li} - T_a\right)} = e^{-\frac{UA}{\rho C_p V}t} \end{aligned}}$$

Analysis of a liquid storage tank (contd.)

$$\boxed{\begin{aligned} q_u &= \dot{m}C_p\left(T_{fo}-T_{fi}\right)=\dot{m}C_p\left(T_{fo}-T_l\right) \\ q_{load} &= \dot{m}_{load}C_p\left(T_l-T_i\right) \end{aligned}}$$

$$\left(\rho VC_p\right)_e\frac{dT_l}{dt}=q_u-q_{load}-\left(UA\right)_t\left(T_l-T_a\right)$$

$$\Rightarrow\left(\rho VC_p\right)_e\frac{dT_l}{dt}=\dot{m}C_p\left(T_{fo}-T_l\right)-\dot{m}_{load}C_p\left(T_l-T_i\right)-\left(UA\right)_t\left(T_l-T_a\right)$$

$$\frac{T_{fo}-T_{fi}}{T_{fo}-T_l}=1-\exp\left[-\frac{\left(UA\right)_e}{\dot{m}C_p}\right]$$

$$q_u=\dot{m}C_p\left(T_{fo}-T_{fi}\right)=\dot{m}C_p\left(T_{fo}-T_l\right)\left[1-\exp\left(-\frac{uA}{\dot{m}C_p}\right)\right]$$

$$\boxed{\left(\rho VC_p\right)_e\frac{dT_l}{dt}=\dot{m}C_p\left(T_{fo}-T_i\right)\left[1-\exp\left(-\frac{UA}{\dot{m}C_p}\right)\right]-\dot{m}_{load}C_p\left(T_l-T_i\right)-\left(UA\right)_t\left(T_l-T_a\right)}$$

When $T_{fo}<T_l$: the flow through the collectors would be stopped and

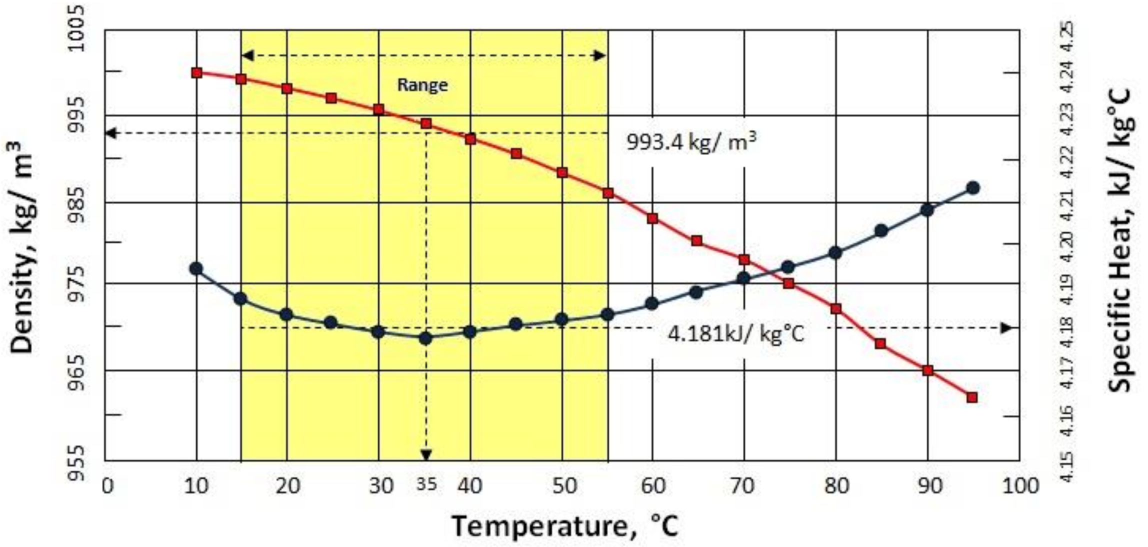
$$\boxed{\dot{m}=0 \text{ and } q_u=0}$$

When no energy is required on the load side,

$$\boxed{\dot{m}_{\text{load}}=0 \text{ and } q_{\text{load}}=0}$$

Stratification in storage tank

Water tanks may operate with significant degrees of stratification (due to density differences), that is, with the top of the tank hotter than the bottom. This allows hot water to be delivered to the load and cool water to return to the collectors.



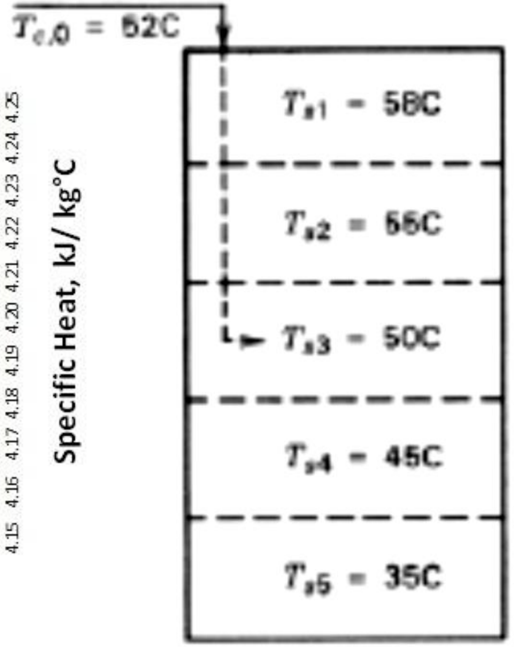
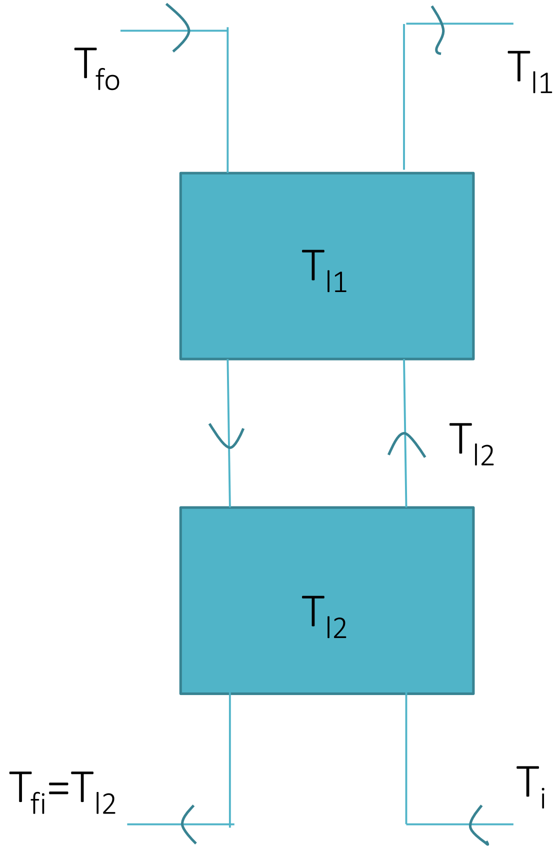


Fig.11. Variation of specific heat and density of water with temperature



Thermal stratification

$$\left(\rho V C_p\right)_{e1}\frac{dT_{l1}}{dt}=\dot{m}C_p\left(T_{fo}-T_{l1}\right)-\dot{m}_{load}C_p\left(T_{l1}-T_{l2}\right)-\left(UA\right)_{t1}\left(T_{l1}-T_a\right)$$

$$\left(\rho V C_p\right)_{e2}\frac{dT_{l1}}{dt}=\dot{m}C_p\left(T_{l1}-T_{l2}\right)-\dot{m}_{load}C_p\left(T_{l2}-T_i\right)-\left(UA\right)_{t2}\left(T_{l2}-T_a\right)$$

- ✓ Heat losses from the tank are reduced
- ✓ Collectors operate at a lower temperature level and delivers a higher collector efficiency

Phase change material(PCM)

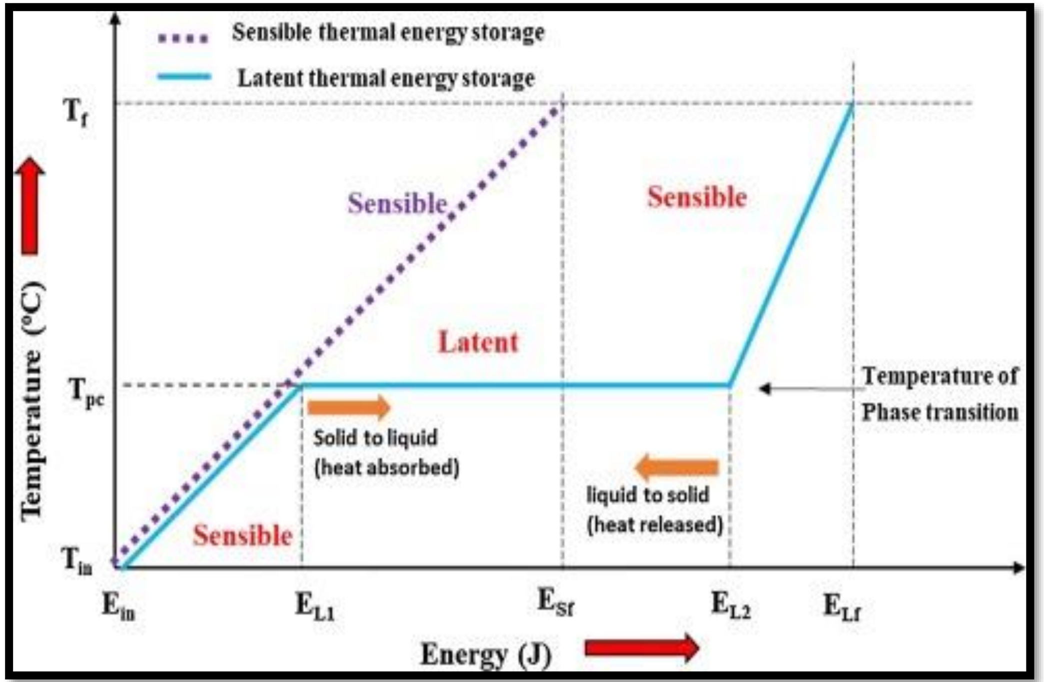


Fig. Constant temperature range for PCM application

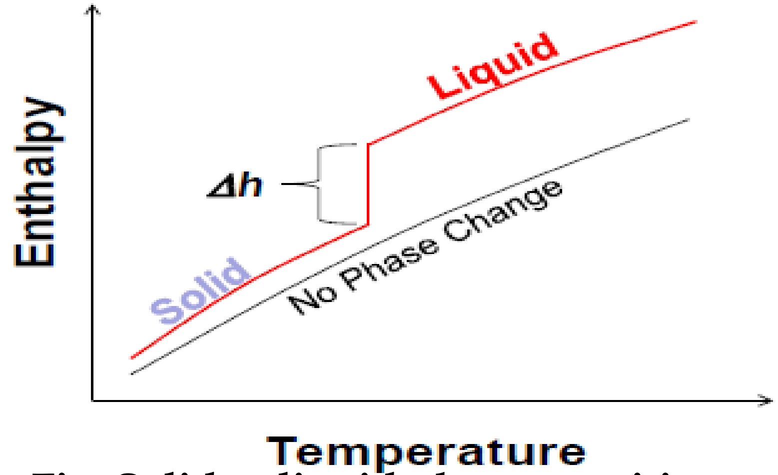


Fig. Solid to liquid phase transition

<u>Properties required for a PCM</u>

- ❑A melting point in the temperature range of the application for which it is being considered.
- ❑A high value of the latent heat of fusion.
- ❑A small volume change during the phase change.
- ❑A negligible amount of super cooling or super heating for phase change to occur.

❑Properties should be stable and should not degrade after repeated cycle (involving melting and solidification).

- ✓ High thermal conductivity
- ✓ Low vapor pressure
- ✓ Non corrosive.

PCMs for space heating applications in buildings

Properties of PCM used for buildings

Type	Melting point (°C)	Heat of fusion (KJ/ kg)
Butyl stearate	19	140
Capric – Launic acid (45-55%)	21	153
Hexadecane	18	236
Heptadecane	22	214
Propyl palmitate	19	186

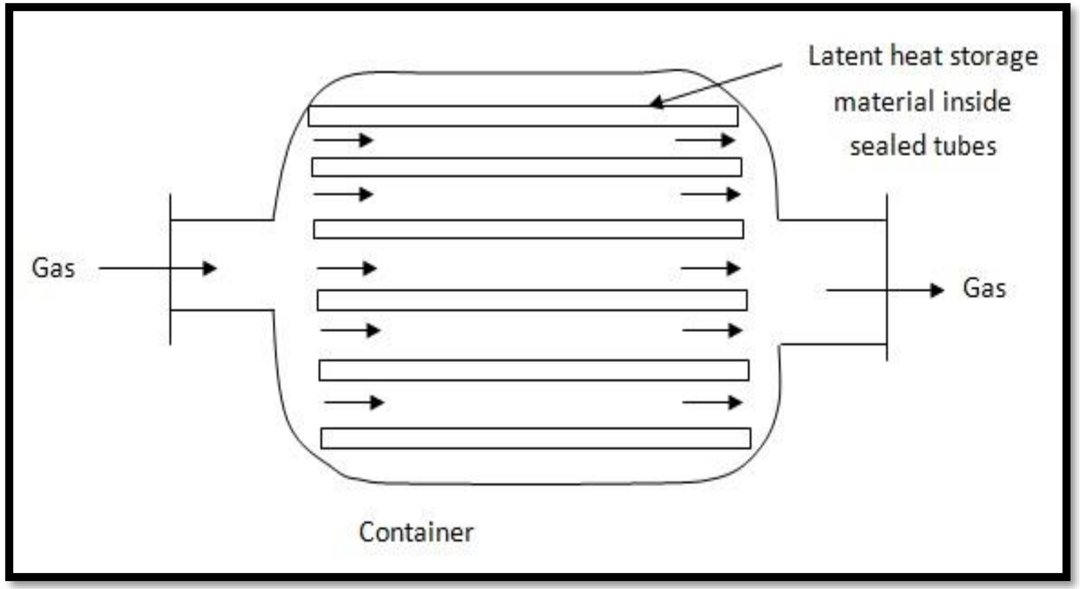


Fig. Design of sealed tube containing PCM

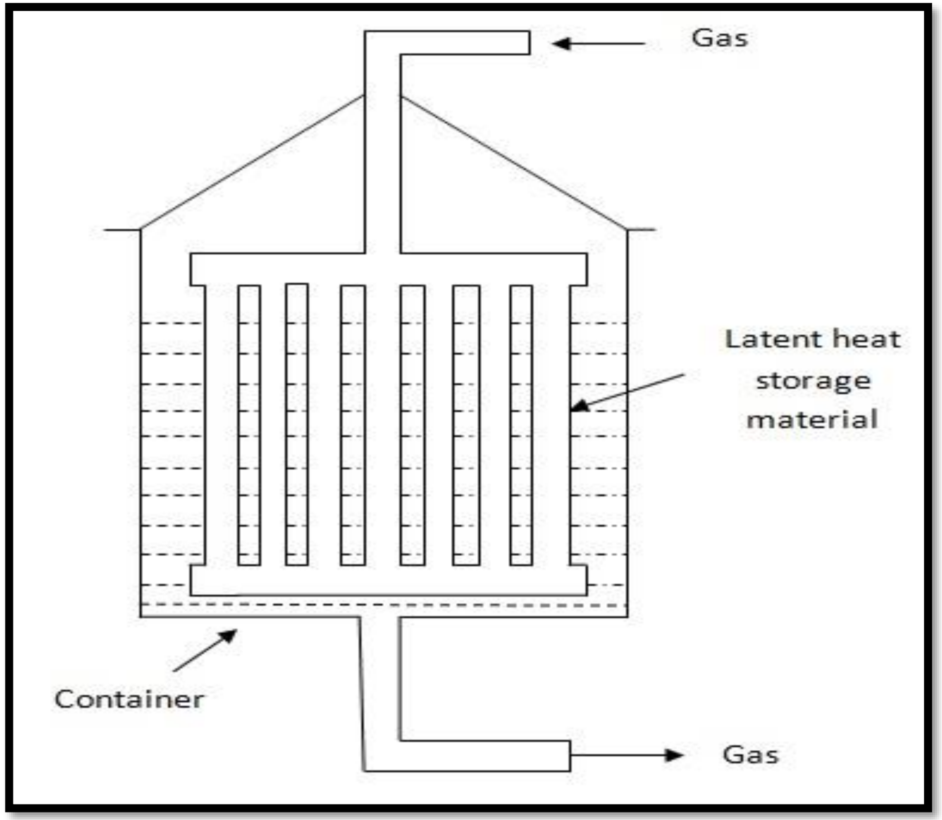


Fig. Design of latent heat storage for buildings

PCM options

	Compound	Melting temperature (°C)	Heat of fusion (KJ/ kg)	Thermal conductivity (W/ m . K)	Density (kg/ m3)
Inorganic	$MgCl_2.6H_2O$	117	168.6	0.057(liquid, 120 °C) 0.694 (solid, 90°C)	1450 (liquid, 120 °C) 1569 (solid, 20°C)
	$Mg(NO_3)_2.6H_2O$	89	162.8	0.490(liquid, 95 °C) 0.611(solid, 37°C)	1550 (liquid, 94 °C) 1636 (solid, 25°C)
	$Ba(OH_2).8H_2O$	48	265.7	0.653(liquid, 85.7 °C) 1.225(solid, 23°C)	1937(liquid, 84 °C) 2070(solid, 24°C)
	$CaCl_2.6H_2\,O$	29	190.8	0.540(liquid, 38.7 °C) 1.088(solid, 23°C)	1562(liquid, 32 °C) 1802(solid, 24°C)
Organic (paraffin)	Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C) 0.346(solid, 33.6°C)	790(liquid, 65 °C) 916(solid, 24°C)
	Polyglycol E600	22	127.2	0.189(liquid, 38.6°C)	1126 (liquid, 25 °C) 1232(solid, 4°C)
Organic (non-paraffin)	Palmitic acid	64	185.4	0.162(liquid, 68.4°C)	850(liquid, 65°C) 989(solid, 24°C)
	Capric acid	32	152.7	0.153(liquid, 38.5°C)	878(liquid, 45°C) 1004(solid, 24°C)
	Caprylic acid	16	148.5	0.149(liquid, 38.6°C)	901(liquid, 30°C) 981(solid, 13°C)
Aromatics	Naphthalene	80	147.7	0.132(liquid, 83.8°C)	976(liquid, 84°C) 1145(liquid, 20°C)

PCM Options (Organic)

Benefits

- ✓ Melts congruently
- ✓ Chemically and physically stable
- ✓ High heat of fusion

Drawbacks

- ➢ More expensive and flammable
- ➢ Low thermal conductivity in solid state
- ➢ Lower heat storage capacity per volume
- ➢ Leakage during phase transition

Solutions

- ✓ Metallic fillers
- ✓ Metal matrix structures
- ✓ Finned tubes

- ✓ Encapsulation

- ✓ Preparation of form-stable material using porous supporting matrix

Encapsulation

- ❑Prevents reactivity towards environment
- ❑Compatible with stainless steel, polypropylene, and polyolefin
- ❑Controls volume when phase change occurs
- ❑ A large improvement in heat transfer rates

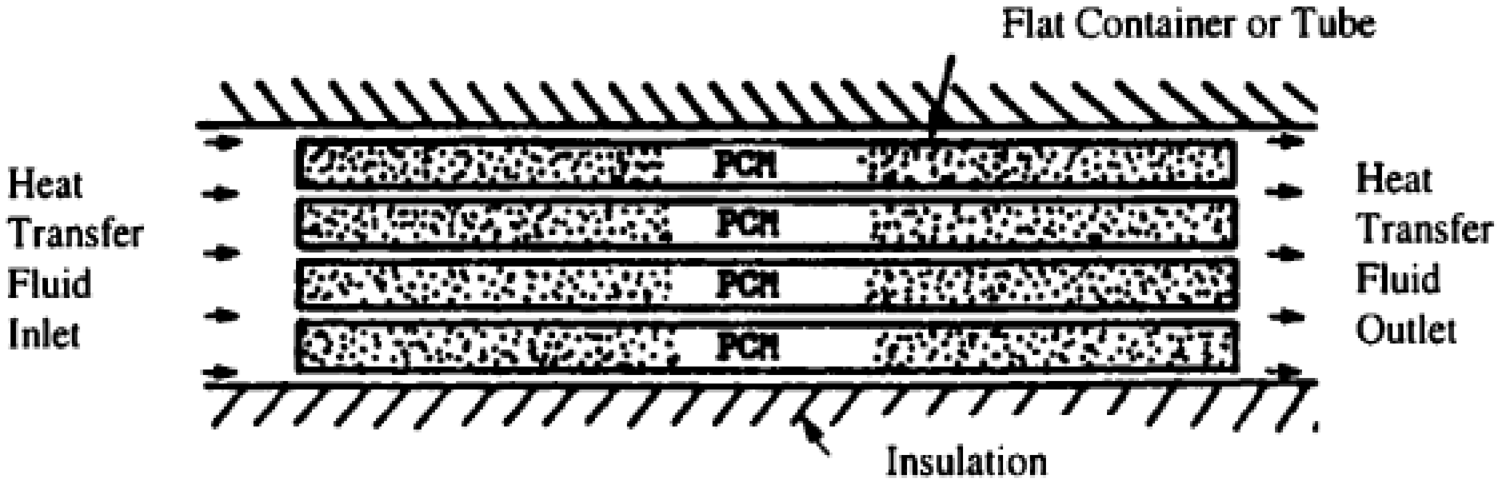


Fig. Encapsulation applied to PCM

(Farid, 2004)

Drawbacks

- ✓ High pressure drop of HTF through the bed
- ✓ High initial cost

Thermochemical storage

- The solar energy to be stored is used to produce a certain endothermic chemical reaction and the products of the reactions are stored.
- When the energy is required to be released, the reverse exothermic reaction is made to take place.
- Suitable for medium or high temperature applications only.

Thermochemical storage reactions

Reaction	Temperature of forward reaction (ºC)	Temperature of reverse reaction (ºC)	Energy stored per unit volume of storage (kJ/m³)
$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	780	610	**209.4 x 10³**
$SO_3 \rightleftharpoons SO_2 + \frac{1}{2}O_2$	1028	590	**460.6 x 10³**
$NH_4HSO_4 \rightleftharpoons NH_3 + H_2O + SO_3$	498	135	**2143.7 x 10³**

Criteria for selection of thermochemical reactions for solar applications

The forward reaction should occur in the temperature range of the solar collectors used.

The reverse reaction should occur in the temperature range in which heat is to be extracted.

The reactions in both directions should be fast and completely reversible with no side reactions which may produce contaminants.

The energy absorbed per unit volume of the products stored should be as large as possible and the product should be in the liquid form.

Two reactions should occur at temperatures which are close to each other. (in this way the collector temperature is minimized and its efficiency maximized).

Summary

- Reliable and affordable energy storage is a prerequisite for using renewable energy.
- Energy storage therefore has a pivotal role in the future.
- Thermal energy storage is imperative to make solar energy more reliable and competitive.
- Further research in phase changing material can improve the efficiency of energy storage.
- Design of the system is also important in optimizing energy storage.