Thermal Energy Storage

1. Sensible Heat
2. Latent Heat
3. Thermocatalytic Decomposition
4. Photocatalytic Decomposition
Solar Ponds

- Large surface area
- Stratification due to buoyancy
  - Warmer fluid at surface
  - Some energy returned to atmosphere via evaporation
  - Partial pressure of H2O usually higher at surface than in atmosphere, reduces evaporation losses

- Some natural salt-water lakes exhibit opposite behavior
  - IT is reversed
  - Lakes have non-uniform salt concentrations
    - Greater concentration at bottom even though it is warmer than surface
  - Solar energy absorbed at deeper layers remains there

- Solar ponds, salt ponds - designed to take advantage of this phenomenon
  - Combined solar collector/energy storage system medium

- El Paso, TX
  - 3350 m² water storage pond near a food canning plant converted to a solar pond in 1986
  - Largest built in Israel in Dead Sea region
  - 6250 m² pond at En Beqek → 150 MW plant → first
  - Now:
    - 40,000 m²
    - 210,000 m²
    - 5 MW Rankine peaking plant
Thermal Energy Storage

Collector - Tsdeliver = ΔT (transport from collector to storage) + ΔT (into storage) + ΔT (storage loss) — 'self-discharge' + ΔT (out of storage) + ΔT (transport from storage to application) + ΔT (into application)

\[ Q_s = (m \cdot C_p) \cdot \Delta T_s \]

Water storage (tank)

- Top of tank hotter than bottom
- Can allow for better over all thermal storage if properly designed

Packed bed storage
- Pebble bed
- Rock pile
- Use heat capacity of bed material to store energy
- Usually air as thermal transfer fluid

Storage of Wells
Table 4.1: Physical properties of some sensible heat storage materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/L)</th>
<th>Heat Capacity (kJ/kg·K)</th>
<th>Thermal Conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (1 bar)</td>
<td>1000</td>
<td>1.09</td>
<td>0.63 at 38°C</td>
</tr>
<tr>
<td>Draw salt (Dow Chemical Co.)</td>
<td>1200</td>
<td>0.90</td>
<td>0.63 at 38°C</td>
</tr>
<tr>
<td>Molten salt (ISKINO)</td>
<td>1420</td>
<td>0.72</td>
<td>0.57 at 38°C</td>
</tr>
<tr>
<td>Sodium (Thermolin 60°C)</td>
<td>1680</td>
<td>0.75</td>
<td>0.57 at 38°C</td>
</tr>
<tr>
<td>Cast iron</td>
<td>720</td>
<td>0.86</td>
<td>0.59 at 38°C</td>
</tr>
<tr>
<td>Dowel (10 mm)</td>
<td>740</td>
<td>0.80</td>
<td>0.63 at 38°C</td>
</tr>
<tr>
<td>Aluminum (1150-1300)</td>
<td>880</td>
<td>0.71</td>
<td>0.63 at 38°C</td>
</tr>
<tr>
<td>Rock</td>
<td>1000</td>
<td>0.70</td>
<td>0.63 at 38°C</td>
</tr>
<tr>
<td>Storage Medium</td>
<td>1000</td>
<td>0.71</td>
<td>0.63 at 38°C</td>
</tr>
</tbody>
</table>

Note: m.p. = melting point.
Table 4.6. Representation from Clark [6].

<table>
<thead>
<tr>
<th>Particle Type</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Crushed rock</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
</tr>
</tbody>
</table>

where \( G \) is the superficial fluid flow rate and Prandtl numbers

where \( D \) is the diameter of the tube and thermal conductivity of the tube and the fluid

where \( A = 0.33 \) for mass flow rate

or the mass flow rate sure drop in packed b
high, which promotes thermal stratification; the costs of the storage material and container are low; the conductivity of the bed is low when there is no airflow; and the pressure drop through the bed can be low.

A major advantage of a packed-bed storage unit is its high degree of stratification. This can be visualized by consideration of a hypothetical situation of a bed initially at a fixed temperature, which has air blown into it at a higher fixed temperature. The temperature profiles in the bed during heating are shown in Figure 8.5.2. The high heat transfer coefficient-area product between the air and pebbles means that high-temperature

![Figure 8.5.1](image1)

**Figure 8.5.1** A packed-bed storage unit.Courtesy of Solaron Corp.

![Figure 8.5.2](image2)

**Figure 8.5.2** Temperature distributions in a pebble bed while charging with inlet air at constant temperature.
\[ \frac{\dot{Q}}{m} = \dot{q}_s = c_p (T_s - T_i) + \lambda + c_l (T_l - T_i) \]

**Solid-to-liquid phase change**

\[ \dot{q}_s = c_p (T_s - T_i) + \lambda + c_l (T_l - T_i) \]

- **Sensible heat to melting point**
- **Sensible heat from melting point**
- **Latent heat of fusion**

**Glutaric Salt** \( \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} \) \[ \rightarrow \text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} + \text{Q} \] \[ \leftrightarrow \text{Na}_2\text{SO}_4 + 10\text{H}_2\text{O} \]

\[ c_s \approx 1950 \text{J/kgK} \]
\[ c_l \approx 3550 \text{J/kgK} \]
\[ \lambda \approx 2.43 \times 10^5 \text{J/kg} \] at 34°C

\[ 1 \text{ kg heated from 25°C to 50°C} \]

\[ \dot{Q}_s = 1950 (30-25) + 2.43 \times 10^5 + 3550 (50-34) = 315 \text{ J/kg} \]

**PCM's have a tendency to degrade with thermal cycling**, partially due to phase separation.
Table 4.3. Physical properties of latent heat storage materials or PCMs

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (wt% by weight)</th>
<th>State</th>
<th>MLI</th>
<th>HML</th>
<th>LMI</th>
<th>LI</th>
<th>Solid (g/L)</th>
<th>Liquid (g/L)</th>
<th>Solid Density (kJ/kg)</th>
<th>Liquid Density (kJ/kg)</th>
<th>Energy Density (kJ/L)</th>
<th>Thermal Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE (Oxidation)</td>
<td>HDPE (70/30)</td>
<td>Liquid</td>
<td>126</td>
<td>28.3</td>
<td>397</td>
<td>505</td>
<td>222</td>
<td>32.4</td>
<td>8.1</td>
<td>1.76</td>
<td>3.32</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td>203</td>
<td></td>
<td>2.88</td>
<td>1.68</td>
<td>1.34</td>
<td>1.63</td>
<td>1.76</td>
<td>2.35</td>
<td>960</td>
<td>814</td>
<td>2300</td>
<td>2295</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td></td>
<td>2.51</td>
<td>1.63</td>
<td>1.34</td>
<td>1.63</td>
<td>1.76</td>
<td>3.62</td>
<td>2265</td>
<td>2140</td>
<td>1960</td>
<td>1950</td>
</tr>
<tr>
<td></td>
<td>347</td>
<td></td>
<td>2.33</td>
<td>1.63</td>
<td>1.34</td>
<td>1.63</td>
<td>1.76</td>
<td>4.50</td>
<td>1900</td>
<td>1780</td>
<td>1600</td>
<td>1590</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td></td>
<td>1.50</td>
<td>1.63</td>
<td>1.34</td>
<td>1.63</td>
<td>1.76</td>
<td>2.25</td>
<td>0.27</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Note: *Composition in percent by weight.

Thermal Energy Storage and Transport
Chemical energy storage

- Thermal decomposition of potassium oxide
  \[ 4 \text{K}_2\text{O} \leftrightarrow 2 \text{K}_2\text{O}_2 + 3\text{O}_2 \]  
  - Heat of decomposition of 21 MJ/kg
  - 300 to 800°C

- Thermal decomposition of lead oxide
  \[ 2\text{PbO}_2 \leftrightarrow 2\text{PbO} + \text{O}_2 \]  
  - 300–360°C
  - Heat of decomposition of 0.26 MJ/kg

- Photochemical decomposition

\[ \text{NO}_2 + \text{photons} \rightarrow \text{NO} + \text{O} \]

\[ \text{A} + \Delta H_\text{f} \leftrightarrow \text{B} + \text{C} \]

- Forward direction is endothermic (heat storage)
- Reverse direction is exothermic (heat release)

\[ Q_s = \text{area} \times \Delta H_\text{f} \]  
  - Amount of thermal energy stored

\[ \text{fraction of mass reacted} \]

- Joseph Priestley, 1774: Mercury oxide
  - Released gas that resulted in brighter candle combustion
  - Mouse lived longer
  - Eventually led to identification of \( \text{O}_2 \)

- Decomposition of:
  - Metal hydrides
  - Oxides
  - Peroxides
  - Ammonium salts
  - Carbonates
  - Alkali trioxides

- Should also include sensible heat
Table 4.4. Properties of thermochemical storage media

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Condition of Reaction</th>
<th>Component (Phase)</th>
<th>Pressure, kPa</th>
<th>Temperature, °C</th>
<th>Density, kg/m³</th>
<th>Volumetric Storage Density, kWh/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgCO₃(s) + 1200 kJ/kg = MgO(s) + CO₂(g)</td>
<td>100</td>
<td>MgCO₃(s)</td>
<td>100</td>
<td>20</td>
<td>1500</td>
<td>187</td>
</tr>
<tr>
<td>Ca(OH)₂(s) + 1415 kJ/kg = CaO(s) + H₂O(g)</td>
<td>100</td>
<td>Ca(OH)₂(s)</td>
<td>100</td>
<td>20</td>
<td>1115</td>
<td>345</td>
</tr>
<tr>
<td>SO₃(g) + 1235 kJ/kg = SO₂(g) + NO₃(g)</td>
<td>100</td>
<td>SO₃(g)</td>
<td>100</td>
<td>45</td>
<td>1900</td>
<td>280</td>
</tr>
</tbody>
</table>

Note: s = solid; l = liquid; g = gas

Goswami, Kreith, and Kreider