Overview on Thermal Storage Systems

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Why storage?

- Cost reduction for solar generated electricity
- Improve availability of solar power plants
Tasks of Storage

- Buffering during transient weather conditions
- Dispatchability or time-shifting
- Increase of annual capacity factor
- More even distribution of electricity production
- Achieve full load operation of the steam cycle at high efficiency
Technical Requirements for Storage Systems

- High energy density (per-unit mass or per-unit volume) in the storage material
- Good heat transfer between heat transfer fluid (HTF) and the storage medium
- Mechanical and chemical stability of storage material
- Chemical compatibility between HTF, heat exchanger and/or storage medium
- Complete reversibility for a large number of charging/discharging cycles
- Low thermal losses
- Ease of control
Design Criteria: Cost

- The cost of the storage material itself
- The heat exchanger for charging and discharging the system
- The cost for the space and the enclosure for the TES
Storage Mechanism

- Sensible heat storage (solid of liquid)
- Latent heat storage
- Chemical Storage
### Solid Storage Materials

<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Temperature</th>
<th>Average density (kg/m³)</th>
<th>Average heat conductivity (W/mK)</th>
<th>Average heat capacity (kJ/kgK)</th>
<th>Volume specific heat capacity (kWh/m³)</th>
<th>Media costs per kg (US$/kg)</th>
<th>Media costs per kWhₜ (US$/kWht)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-rock-mineral oil</td>
<td>200</td>
<td>1,700</td>
<td>1.0</td>
<td>1.30</td>
<td>60</td>
<td>0.15</td>
<td>4.2</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>200</td>
<td>2,200</td>
<td>1.5</td>
<td>0.85</td>
<td>100</td>
<td>0.05</td>
<td>1.0</td>
</tr>
<tr>
<td>NaCl (solid)</td>
<td>200</td>
<td>2,160</td>
<td>7.0</td>
<td>0.85</td>
<td>150</td>
<td>0.15</td>
<td>1.5</td>
</tr>
<tr>
<td>Cast iron</td>
<td>200</td>
<td>7,200</td>
<td>37.0</td>
<td>0.56</td>
<td>160</td>
<td>1.00</td>
<td>32.0</td>
</tr>
<tr>
<td>Cast steel</td>
<td>200</td>
<td>7,800</td>
<td>40.0</td>
<td>0.60</td>
<td>450</td>
<td>5.00</td>
<td>60.0</td>
</tr>
<tr>
<td>Silica fire bricks</td>
<td>200</td>
<td>1,820</td>
<td>1.5</td>
<td>1.00</td>
<td>150</td>
<td>1.00</td>
<td>7.0</td>
</tr>
<tr>
<td>Magnesia fire bricks</td>
<td>200</td>
<td>3,000</td>
<td>5.0</td>
<td>1.15</td>
<td>600</td>
<td>2.00</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Concrete Storage

- tested at small scale
- low cost
- long-term stability?
Process Integration of Concrete Storage
## Liquid Material

<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Temperature</th>
<th>Average density</th>
<th>Average heat conductivity</th>
<th>Average heat capacity</th>
<th>Volume specific heat capacity</th>
<th>Media costs per kg</th>
<th>Media costs per kWhₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold (°C)</td>
<td>Hot (°C)</td>
<td>(kg/m³)</td>
<td>(W/mK)</td>
<td>(kJ/kgK)</td>
<td>(US$/kg)</td>
<td>(US$/kWh)</td>
</tr>
<tr>
<td>Liquid media</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral oil</td>
<td>200</td>
<td>300</td>
<td>770</td>
<td>0.12</td>
<td>2.6</td>
<td>55</td>
<td>0.30</td>
</tr>
<tr>
<td>Synthetic oil</td>
<td>250</td>
<td>350</td>
<td>900</td>
<td>0.11</td>
<td>2.3</td>
<td>57</td>
<td>3.00</td>
</tr>
<tr>
<td>Silicone oil</td>
<td>300</td>
<td>400</td>
<td>900</td>
<td>0.10</td>
<td>2.1</td>
<td>52</td>
<td>5.00</td>
</tr>
<tr>
<td>Nitrite salts</td>
<td>250</td>
<td>450</td>
<td>1,825</td>
<td>0.57</td>
<td>1.5</td>
<td>152</td>
<td>1.00</td>
</tr>
<tr>
<td>Nitrate salts</td>
<td>265</td>
<td>565</td>
<td>1,870</td>
<td>0.52</td>
<td>1.6</td>
<td>250</td>
<td>0.50</td>
</tr>
<tr>
<td>Carbonate salts</td>
<td>450</td>
<td>850</td>
<td>2,100</td>
<td>2.0</td>
<td>1.8</td>
<td>430</td>
<td>2.40</td>
</tr>
<tr>
<td>Liquid sodium</td>
<td>270</td>
<td>530</td>
<td>850</td>
<td>71.0</td>
<td>1.3</td>
<td>80</td>
<td>2.00</td>
</tr>
</tbody>
</table>
Mineral Oil Storage

- SEGSI
- HTF: Mineral Oil
- 2-Tank Mineral Oil Storage
- Max Temp.: 307°C
- Capacity: 115 MWh
Process Scheme of SEG S I
Molten Salt Storage

- 2 Tank Molten Salt
- Nitrate Salt Mixture
- Salt was also HTF
- Max Temp. 565°C
- Capacity: 105 MWh
Process Scheme for SEGS plant with 2 Tank TES
Next Step Thermocline Storage
# Phase Change Material

<table>
<thead>
<tr>
<th>Storage Medium</th>
<th>Temperature</th>
<th>Average density</th>
<th>Average heat conductivity</th>
<th>Average heat capacity</th>
<th>Volume specific heat capacity</th>
<th>Media costs per kg</th>
<th>Media costs per kWh&lt;sub&gt;t&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold (°C)</td>
<td>Hot (°C)</td>
<td>(kg/m³)</td>
<td>(W/mK)</td>
<td>(kJ/kgK)</td>
<td>(US$/kg)</td>
<td>(US$/kWh&lt;sub&gt;t&lt;/sub&gt;)</td>
</tr>
<tr>
<td>Phase change media</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaNO₃</td>
<td>308</td>
<td></td>
<td>2,257</td>
<td>0.5</td>
<td>200</td>
<td>125</td>
<td>0.20</td>
</tr>
<tr>
<td>KNO₃</td>
<td>333</td>
<td></td>
<td>2,110</td>
<td>0.5</td>
<td>267</td>
<td>156</td>
<td>0.30</td>
</tr>
<tr>
<td>KOH</td>
<td>380</td>
<td></td>
<td>2,044</td>
<td>0.5</td>
<td>150</td>
<td>85</td>
<td>1.00</td>
</tr>
<tr>
<td>Salt-ceramics (NaCO₃-BaCO₃/MgO)</td>
<td>500-850</td>
<td></td>
<td>2,600</td>
<td>5.0</td>
<td>420</td>
<td>300</td>
<td>2.00</td>
</tr>
<tr>
<td>NaCl</td>
<td>802</td>
<td></td>
<td>2,160</td>
<td>5.0</td>
<td>520</td>
<td>280</td>
<td>0.15</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>854</td>
<td></td>
<td>2,533</td>
<td>2.0</td>
<td>276</td>
<td>194</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Phase Change Material Experiments

- only lab scale experiments
Process Scheme for SEGS with PCM-Storage
Chemical Storage

- only lab scale experiments
- or
- for different applications (Dish)
Summary

- Three storage options offer favourable cost
  - Salt Storage (2-Tank and Thermocline)
  - Concrete (or compound material)
  - Phase change material

- No reliable information available about cost of chemical storage

- 2-Tank molten salt storage seems to be most advanced system and ready for realization
Overview on Current European Work

• 2-Tank Molten Salt Storage
  AndaSol-Project  Herrmann/Geyer/Kistner

• Concrete or Compound Material
  Update on the European concrete TES program
  Tamme

• Phase Change Material
  Phase Change Storage/Storage for DISS
  Tamme/Pitz-Paal