Experimental Investigations on Cold Recovery Efficiency of Packed-bed in Cryogenic Energy Storage System

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Introduction

• Significant attention on large-scale energy storage due to penetration of renewable energy sources [1]
• Existing large-scale energy storage systems: Pumped-hydro, Compressed Air Energy Storage (CAES) etc. [1,2,3]
• Limitations of such systems:
  • Coupled system
  • Location specific
  • High cost

<table>
<thead>
<tr>
<th>Type of storage</th>
<th>Turnaround efficiency</th>
<th>Location specific</th>
<th>Capital cost (S/kW)</th>
<th>Discharge time at rated power</th>
<th>Power rating (MW)</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro</td>
<td>87</td>
<td>Yes</td>
<td>2700-4600</td>
<td>12 hrs</td>
<td>250 to &gt; 1000</td>
<td>30 years</td>
</tr>
<tr>
<td>CAES</td>
<td>54-88</td>
<td>Yes</td>
<td>500-1500</td>
<td>2-24 hrs</td>
<td>15 to 400</td>
<td>35 years</td>
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<tr>
<td>SMES</td>
<td>90</td>
<td>No</td>
<td>700-2000</td>
<td>100 s to 5-10 hrs</td>
<td>100-200</td>
<td>&gt; 30,000 cycles</td>
</tr>
<tr>
<td>Li-ion batteries</td>
<td>90 (DC)</td>
<td>No</td>
<td>4000-5000</td>
<td>15 mins to several hrs</td>
<td>5</td>
<td>15 years</td>
</tr>
<tr>
<td>CES</td>
<td>&gt; 70</td>
<td>No</td>
<td>400-1500</td>
<td>6-8 hrs</td>
<td>&gt; 100</td>
<td>35 years</td>
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</table>
Cryogenic Energy Storage (CES): A potential alternative as it is:

- Decoupled system
- With large power generation capability
- With low picking time
- Scalable
- With comparable cost, and
- With mature equipment technologies [2,3]

Three subsystems:

- Charging or the liquefaction process,
- Storage of liquid, and
- Discharging or the power cycle.
CES systems:

- Low turnaround efficiency of around 30% or less [4-5]
- Suggested method to improve the efficiency [5,6]:
  - Storage of available heat/refrigeration using packed-bed thermal storage
  - Use heat of compression by Organic Rankine Cycle to produce waste to power
  - Using industrial waste-heat for superheating in power cycle etc.
Introduction

Packed-bed thermal energy storage:

• A key auxiliary sub-system for recovery of cold from evaporator-superheater in power cycle
  • Used for storing solar thermal energy
  • Common bed materials: Rocks, metals
  • Air as heat transfer fluid [7]
  • Temperature range from room temperature to higher

• A few studies on such energy storage at low temperature
The objectives are to develop the experimental setup and perform the following.

• Measure the temperature profiles inside the packed-bed thermal storage during both charging and discharging processes

• Determine the storage efficiency during full-load and part-load with prolonged standby operation of the system
Methodology

• Performed two sets of experiments:
  1. Full-load operation with bed cut-off temperature of 150 K
  2. Partial charging of the bed or part-load with prolonged standby time and cut-off temperature of 175 K

• Used three non-dimensional parameters:
  • Non-dimensional temperature ($\theta$)
    \[ \theta = \frac{T - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}} \]
  • Non-dimensional length ($x/L$)
  • Non-dimensional time ($t/\tau$).

• The equation for storage efficiency calculation [8]:
  \[
  \eta_{PB} = \frac{\int_{x_{\text{in}}}^{x_{\text{out}}} \int_{T_{c,L,\text{min}}}^{T_{c,L,\text{max}}} C_s L(T,x)dTdx - \int_{x_{\text{in}}}^{x_{\text{out}}} \int_{T_{c,0,\text{min}}}^{T_{c,0,\text{max}}} C_{s,0}(T,x)dTdx}{L \int_{T_{c,\text{in}}}^{T_{dch,\text{in}}} C_s(T)dT}
  \]
Experimental

- **Equipment:**
  - Packed-bed,
  - Air compressor,
  - A liquid nitrogen dewar,
  - Copper coil heater,
  - Two gate valves (V03, V04)
  - Two needle valves (V02, V05)

- **Instrumentation:**
  - The inlet and outlet pressures (PI01, PI02) using dial gauges and temperatures (TI01, TI02, TI03) using platinum RTDs
  - The temperatures inside the packed-bed including the ullage volume above it using platinum RTDs placed axially interfaced with DT80, dataTaker data acquisition system
  - Uncertainty of the temperature sensors in 78 K to 373 K range: ±2 K
## Specifications of the equipment of the process

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameter</th>
<th>Value</th>
<th>Equipment</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater</td>
<td>No. of tubes</td>
<td>3/5</td>
<td>Temperature sensor</td>
<td>Type</td>
<td>Pt100</td>
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<tr>
<td></td>
<td>Tube length</td>
<td>85 cm</td>
<td></td>
<td>Uncertainty</td>
<td>±2 K</td>
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<tr>
<td></td>
<td>Tube ID/OD</td>
<td>1.5 cm/1.9 cm</td>
<td></td>
<td>Number</td>
<td>7</td>
</tr>
<tr>
<td>Packed-bed</td>
<td>Height</td>
<td>40 cm</td>
<td>Pressure sensor</td>
<td>Type</td>
<td>Dial gauge</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>15 cm</td>
<td></td>
<td>Range</td>
<td>0-4 barg</td>
</tr>
<tr>
<td></td>
<td>Ullage height</td>
<td>10 cm</td>
<td></td>
<td>Uncertainty</td>
<td>±2%</td>
</tr>
<tr>
<td></td>
<td>Operating pressure</td>
<td>1.5 bar</td>
<td>Gas buffer</td>
<td>Max. pressure</td>
<td>12 barg</td>
</tr>
</tbody>
</table>
**Experimental**

- **Charging process**: Superheated liquid to 150 K/175 K for cooling down the bed
- **Discharging process**: Pressurized air to warm up the packed-bed to room temperature
Experimental: Process flow diagram with instrumentation

Left: Layout of the experimental setup; Right: Bed height and placement of RTDs inside the vessel
Experimental

Packed-bed

V3 V5 V4 V2

Air compressor

Dewar

Copper coil heater
Experimental: Description of the packed-bed

- Used a vacuum insulated vessel of inner volume 27.3 ltrs. with required bi-directional inlet and outlet ports as packed-bed
  - Bed height ($L$): 32 cm
  - Bed diameter ($D$): 15 cm
  - Ullage space: 10 cm
- Granite pebbles as packing material with dimensions between 12.5 mm×12.5 mm and 10 mm×10 mm
  - Average equivalent diameter ($d$): 11.25 mm.
  - Average density: 2688 kg/m$^3$
  - Mean average heat capacity: 0.7 kJ/kg-K
  - The porosity of the bed ($\varepsilon$): 0.38
Results and discussions

• Conducted experiments on two different operating scenario
  • **Full-load**: Cooling down the entire bed to the bed cut-off temperature of 150 K; Charging time: 6 hrs., Standby: 5 min; Discharging time: 4.5 hrs
  • **Part-load with prolonged standby period**: Cooling down a part of the bed to the bed cut-off temperature of 175 K; Charging time: 2 hrs, Standby: 2 hrs, Discharging time: 2 hrs.

• Constant flow rate to the packed-bed
• Ambient temperature: 31.9°C during full-load, 33°C during part-load
• Compressor discharge pressure: 1.5 bar
Results and discussions: Operation under full-load

Temperature profile inside packed-bed operating under full-load condition with cut-off temperature of 150 K

- Demonstrated the process of storage and utilization with a storage efficiency of 94.71%
- Reasons behind the losses:
  - High heat in-leak due to higher charging time leading to loss of stored refrigeration
  - Variation of flow rate during cooling down reduced heat transfer between fluid and solid periodically
Results and discussions: Operation under full-load

Temperature distribution inside the packed-bed during the charging cycle

Temperature distribution inside the packed-bed during the discharging cycle
Observations

• Typical thermocline profile inside the bed both during charging and discharging processes

• Due to lower flow rate during charging process, lower rate of reduction in temperature in this period

• Overall pressure drop of 30 kPa in the process (including the bed, transfer lines and heater)

• The pressure drop in the bed varied in a range of ±5 kPa
  • Flow rate varied periodically with little effect on the performance of the bed deep inside

• Variation in ullage volume temperature ($T_4$) after reaching below 190 K
  • Temperature at adjacent to ullage space ($T_5$) also increased proportionally.
  • After $T_4$ reached above 190 K, both $T_4$, $T_5$ again started reducing
Results and discussions: Operation under part-load

Temperature profile inside packed-bed operating under part-load and prolonged standby condition with cut-off temperature of 175 K

- Non-uniform temperature profile of the bed due to partial cooling,
  - The lower part of the bed 10% warmer than the upper part
- Increase in bed temperature during standby period:
  - Due to the heat in-leak in the bed
  - Due to conduction inside the bed
- Settling of refrigeration
  - Due to presence of a finite temperature gradient inside the bed from the upper part to the lower part of the bed
  - Increased the bed cut-off temperature by 30%.
Results and discussion: Operation under part-load

- Low storage efficiency of 64.57% due to:
  - Settling of refrigeration together
  - Heat in-leak during standby period
- Highest rate of increase in temperature at:
  - Ullage space
  - Inside the bed: Locations adjacent to ullage space
- Pressure drop in the process remained constant at 0.3 bar
- Summary of the two sets of experiments:

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$T_{\text{min}}$ (K)</th>
<th>Storage efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-load with 5 mins standby</td>
<td>305</td>
<td>154</td>
<td>94.71</td>
</tr>
<tr>
<td>Part-load with 2 hrs standby</td>
<td>306</td>
<td>175</td>
<td>67.57</td>
</tr>
</tbody>
</table>
Conclusions

• Developed an experimental setup to investigate the performance of such packed-bed with granite pebbles
  • Conducted two sets of experiments
• Full-load operation:
  • A storage efficiency as high as 95%
  • Uniform temperature profile inside the entire bed at the end of charging cycle
  • Flow instability, high ullage space temperature fluctuation below 190 K
• Part-load and prolonged standby operation:
  • Storage efficiency reduced to 65%
  • Observed settling of refrigeration from the bottom of the bed to upper locations
• Efforts will be made to identify the effects of such factors by varying the ullage space, using different standby times etc.
THANK YOU!

Any questions?
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