Experimental investigation of a thermally integrated Carnot battery using a reversible heat pump/organic Rankine cycle

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May 24– 28, 2021
Introduction

Context

- **Intermittent nature of renewable energy** sources => need for energy storage (large grid balancing, development of micro grids).
- **Batteries** (straightforward solution):
  - Cost (rare materials)
  - Lifespan (<20 years)
  - Environmental footprint
- **Gravity Energy Storage, PHES, CAES**: site dependent.
- **Pumped Thermal Energy Storage (PTES or Carnot battery)** is a promising alternative to store electricity.
Carnot battery = system primarily used to store electricity

- **Charging**: electricity is used to establish a temperature difference between 2 reservoirs (high and low temp.) by means of a HP.
- Electricity is therefore stored as thermal exergy.
- **Discharging**: heat flows from high to low temp. reservoirs and part is converted into electricity by a HE.

**Round-trip efficiency**: \( \varepsilon_{rt} = \frac{E_{he}}{E_{hp}} \)

- Different technologies of HP and HE: vapor compression systems, Brayton cycles, electrical heater.
- Different technologies of thermal energy storage for the heat reservoirs.
- Environment to replace one of the heat reservoirs.
Introduction

Concept

- **Rankine** (vapor compression heat pump + Rankine cycle) PTES vs **Brayton** PTES:
  - larger energy density
  - lower temperatures of TES
    - use of PCM,
    - lower ambient losses,
    - simpler design of machines,
    - uses of off-the-shelf HVAC components (MW-scale storage could easily be built)
  - Similar max roundtrip efficiency of 62-65%

- Other performance criteria to consider: energy and power densities in [kWh/m\(^3\)] and [kW/m\(^3\)].
Performance can be improved by integrating waste heat into the process (Heat Pump + ORC configuration is well suited for low-grade waste heat integration): TIPTES (Thermally Integrated Pumped Thermal Energy Storage).

\[ \varepsilon_{rt} = \eta_{TES} \cdot COP_{HP} \cdot \eta_{RC} \]
Cost of the system can be reduced by mutualizing components of the Heat Pump and ORC.
Principle of operation of a Carnot battery with a reversible HP/ORC system with waste heat integration.

\[ \varepsilon_{rt} = \eta_{TES} \left( \frac{COP_{HP}}{Q_{cd,HP}} \right) \cdot (\eta_{RC} Q_{ev,RC}) = \eta_{TES} \cdot COP_{HP} \cdot \eta_{RC} \]

Rem: a second law-efficiency could be used to consider the difference of thermodynamic quality of heat and electricity.
Agenda of the presentation

1. Introduction
2. Experimental set-up
3. Results
4. Conclusions
Experimental set-up
Layout
Experimental set-up

Components

- Mechanical scroll
  Variable speed
  VR=2.2
  Swept volume = 121 cm³

- Plate heat exchangers
  25 kW

- Hot and cold water storage
  Perfect stratification
  2X900 L

- Plunger pump
  70 g/s

- Manual expansion valve
Experimental set-up

Sensors
Experimental set-up
Performance criteria

- Overall performance: COP of Heat Pump and efficiency of ORC.

\[
COP = \frac{\dot{Q}_{cd,r,oil}}{\dot{W}_{cp,el}}
\]

\[
\eta_{global} = \frac{\dot{W}_{exp,el} - \dot{W}_{pp,el}}{\dot{Q}_{ev,r,oil}}
\]

- Compressor/expander performance: isentropic efficiency, volumetric efficiency/filling factor.

\[
\varepsilon_{cp,is} = \frac{\dot{m}_r(h_{r,cp,ex,is} - h_{r,cp,su}) + \dot{V}_{oil}(p_{cp,ex} - p_{cp,su})}{\dot{W}_{cp,el}}
\]

\[
\varepsilon_{cp,vol} = \frac{\dot{V}_{cp,su,tot}}{\dot{V}_{cp,th}}
\]

\[
\varepsilon_{exp,is} = \frac{\dot{W}_{exp,el}}{\dot{m}_r(h_{r,exp,su} - h_{r,exp,ex,is}) + \dot{V}_{oil}(p_{exp,su} - p_{exp,ex})}
\]

\[
FF_{exp} = \frac{\dot{V}_{exp,su,tot}}{\dot{V}_{exp,th}}
\]
Agenda of the presentation

1. Introduction
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Results
Range of operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ORC</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator thermal power [W]</td>
<td>[8423-18183]</td>
<td>[1203-13351]</td>
</tr>
<tr>
<td>Condenser thermal power [W]</td>
<td>[725-16231]</td>
<td>[1326-14495]</td>
</tr>
<tr>
<td>Evaporation pressure [bar]</td>
<td>[3.4-5.8]</td>
<td>[0.65-4.9]</td>
</tr>
<tr>
<td>Condensation pressure [bar]</td>
<td>[1.1-1.9]</td>
<td>[1.6-7.2]</td>
</tr>
<tr>
<td>Mass flow rate [kg/s]</td>
<td>[0.034-0.079]</td>
<td>[0.007-0.084]</td>
</tr>
<tr>
<td>Subcooling [K]</td>
<td>[6.2-8.8]</td>
<td>[4.1-28.9]</td>
</tr>
<tr>
<td>Superheating [K]</td>
<td>[4.0-25.7]</td>
<td>[3.3-6.3]</td>
</tr>
</tbody>
</table>

- 62 steady-state points in ORC mode and 60 in HP mode.
- Large range of operating conditions.
- All raw data are provided
- Energy residuals on systems and components are checked.
Results
Global performance

- Net electrical power and efficiency increase with temperature lift.
- Lower performance than expected (expander efficiency to be improved).

\[ \text{Temperature lift} \ [K] = |T_{\text{cond}} - T_{\text{ev}}| \]

- Very high COP at low temperature lift.

ORC

Heat Pump
Results
Scroll machine performance

**ORC (expander)**

- Scroll mech. power
- Scroll efficiency
- Scroll filling factor

Lesser impact of leakages

64%

**Heat Pump (compressor)**

- Scroll mech. power
- Scroll efficiency
- Scroll volumetric efficiency

75%
Conclusions

- **Prototype** of innovative technology to store electricity at low cost with a reversible HP/ORC Carnot battery is presented.
- Acceptable performance of components with *margin for improvement*.
- Roundtrip efficiency of **72.5%** (ORC efficiency of 5% (lift: 49 K) and COP of HP of 14.4 (lift: 8 K)).
- Roundtrip electrical energy ratio larger than 100% could be achieved by
  - Improving design of volumetric machine
  - Improving the control, improving thermal insulation
- Transient tests should be conducted to assess the *dynamics of the system* and the services that could be provided to the electricity grid (and on which time scale).
Thank you for your attention!