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Heat & Electricity Storage

Storage of Heat WP1

- **ETHZ**: H. Haselbacher
  - AACAES, **high temperature** heat storage

- **EPFL**: S. Haussener
  - **High temperature** heat storage, multi-physics simulations

- **OST**: P. Gantenbein
  - Ice storage, sorption based seasonal heat storage

- **HSLU**: J. Worlitschek
  - Latent and sensible low temperature heat storage

- **SUPSI**: M. Barbato
  - **High temperature** heat storage, simulation and testing

- **Empa**: L. Baldini
  - Sorption based seasonal heat storage

www.sccer-hae.ch
Motivation for High-Temperature Heat Storage

• Industrial heat heavily dependent on fossil fuels

• Globally, half of industrial heat demand is estimated to be high-temperature (>400°C):
  – Iron and steel subsector accounts for a large part: blast furnace pig iron production requires temperatures up to 1300°C
  – Cement production requires 1400°C
  – Aluminum smelting requires 1000°C

• Valuable heat that should be recovered

• Difficult to obtain from renewable sources

• Predicted to significantly growth
Motivation for High-Temperature Heat Storage

- Relevant also for power production and storage
  - For example, concentrated solar power with high-temperature heat storage can operate 24 hours
  - Advanced adiabatic compressed air energy storage (AA-CAES)

AA-CAES interesting for Switzerland:
- Hydro(-storage) capacity limit reached
- Caverns and tunnel available
- Competences on tunnel/cavern construction

Image adapted from M. Treuthardt, "Druckluftbatterie in den Alpen", Tages-Anzeiger
Advanced adiabatic compressed air energy storage (AA-CAES) uses the heat developed during compression (in contrast to diabatic), which allows for significant improvement of efficiency (~75% instead of ~55%).

- Sustainability of AA-CAES comparable or advantageous to pumped hydro energy storage (~2 g CO₂/kWh)
- Underground installations do not interfere with environment
- Has to act in secondary reserve market, requiring robust and controllable operation
Plant Modelling

- Model development

1D TES code

AA-CAES model

C & T efficiency maps

C & T idles and power ramps

Dry air
Ideal gas

Plant power schedule

Plant Modelling
Plant Modelling

- Model **validation** with data from Huntorf CAES plant and Pollegio AA-CAES pilot plant (adiabatic compression mimicked by heater)

![Diagram of plant components and processes]

![Graphs showing temperature and pressure changes over time, with 'Experiments' and 'Simulation' labels]
• Analytical plant model
  • First known complete model
  • Allows derivation of closed-form expressions for key performance indicators
  • Plant efficiency:

\[
\eta = \eta_{\text{mot}} \eta_{\text{gen}} \eta_{\text{m}}^2 f_\eta,
\]

\[
f_\eta = \frac{T_2}{T_{\text{atm}}} \frac{T_{\text{atm}}}{T_3} \eta_{s,\text{lpt}} f_{\text{lpt}} + \eta_{s,\text{hpt}} f_{\text{hpt}}
\]

\[
\frac{P_{\text{pcav}}}{P_{\text{atm}}} \approx \left( \frac{\gamma}{2\gamma - 1} \frac{\eta_{s,\text{lpc}}}{\eta_{s,\text{hpc}}} \frac{T_3}{T_{\text{atm}}} \right)^{\frac{\gamma}{\gamma - 1}} \sqrt{\frac{P_{\text{pcav,max}}}{P_{\text{atm}}}}
\]

P. Roos, A. Haselbacher, “Analytical modeling of advanced adiabatic compressed air energy storage”, in preparation
Potential Plant Locations

• Geomechanical investigation of detailed plant locations and layouts

G. Anagnostou et al., "AASD – Abdichtung und Auslegung von Speicherhohlräumen für Druckluftspeicherkraftwerke", Final project report, SFOE, October 2020

Detailed investigation of four plant configurations in Grimsel area, two based on caverns (K) and two on shafts (S)
Potential Plant Layout

- Geomechanical investigation of detailed plant locations and layouts (cont.)

G. Anagnostou et al., "AASD – Abdichtung und Auslegung von Speicherhohlräumen für Druckluftspeicherkraftwerke", Final project report, SFOE, October 2020
Importance of Thermal Energy Storage Performance

- Effect of thermal storage

Multi-tank TES without thermocline control:
Discharging power not constant, complicates grid integration

Multi-tank TES with thermocline control:
Discharging power constant, simplifies grid integration

Can be achieved by complex thermocline control or alternatively by incorporating latent heat storage

P. Roos, A. Haselbacher, “Thermocline control through multi-tank thermal-energy storage systems”, accepted for publication, Applied Energy, 2020
P. Roos, P. Gassmann, A. Haselbacher, “Simulation and optimization of advanced adiabatic compressed air energy storage plants”, in preparation
Combined Latent/Sensible Heat Storage

- Phase change material unit acts as «stabilizer» of outflow conditions

- Metal-based phase change media to increase rate of charging and discharging

- Previously, I discussed the degradation issue with encapsulated metal phase change media
  → One possible solution: application of diffusion barrier (coating)
Degradation in Encapsulated PCMs

• Developed mass transport model provides insights into degradation effect and shows that there is a complex interplay between melt volume, solubility, dissolution, and diffusivity than can allow for prolonged operational lifetime

• Electrochemical battery equivalent → Operational conditions recommendation that lead to best lifetime

Binder, EPFL PhD thesis, 2019
Heat Transfer Limitations

- Natural convection in melt – A heat transfer analysis
- Completion of 2D/3D phase change modeling framework combining enthalpy porosity method and Volume of Fluid method
- Generalization through non-dimensionalization

Natural convection within PCM not limiting, instead forced convection around

Heat Transfer Limitations

- Forced convection around ePCM:
  Approach 1: Complex porous structures with large interface area

- Find optimal structure for fast dis/charging high-temperature heat storage

Phase change simulation of the randomly generated macro-porous latent heat storage

Wall heat flux in front and rear view

Heat Transfer Limitations

- Forced convection to PCM:
  Approach 2: Ceramic fins for increased performance

![Diagram showing heat transfer limitations](image)

Large-Scale Test of Approach 2

• Best structure of porous media?
• From the numerical model to the real foam by indirect additive manufacturing

Performance in larger-scale thermal energy storage:

*Rezaei, EPFL/PhD thesis, 2019*
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