Modelling and Simulation of High Temperature TES Systems

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AA-CAES: schematic

Compressor

Motor/Generat or

Turbine

TES

Compressed air storage (Cavern)
AA-CAES: load phase

Electrical power from the grid

Compressor

Electric Motor

Air from ambient is compressed

TES

Thermal energy is stored into the TES

Cavern

Cold compressed air goes into the cavern
AA-CAES: discharge phase

High pressure air is extracted from the cavern

TES

High enthalphy air feeds the turbine

Generator

Electrical energy goes back to the grid

Turbine

NO FUEL NEEDED

Thermal energy is recovered making air flowing throughout the TES
AA-CAES: discharge phase

TES
Packed bed TES working principle

- One tank TES
- Sensible Energy
- Rocks as storage material
- Air as HTF
TES Modeling and Simulation
Modeling packed beds: Porous Media Approach

\[ D_p \]
\[ \varepsilon = \frac{V_{void}}{V_{tot}} \]
\[ k_e \]
\[ v = -\frac{K}{\mu} \frac{dp}{dx} \]

- Solid Phase
- Fluid Phase
- Packed Bed
- Porous Medium
Porous Media Approach: Energy Equation

\[
\frac{\partial}{\partial t} \left[ \varepsilon \rho_f e_f + (1 - \varepsilon) \rho_s e_s \right] + \nabla \cdot [\mathbf{v}(\rho_f e_f + p)] = \nabla \cdot \left[ k_{eff} \nabla T - \left( \sum_i h_i J_i \right) + (\mathbf{T} \cdot \mathbf{v}) \right] + S_f^h
\]

- Index \(s\) stays for solid and \(f\) for fluid
- valid with Thermal Equilibrium assumption \(T_s = T_f\)
- \(\varepsilon\) is the porosity or void fraction
- \(k_{eff}\) is the Effective Thermal Conductivity.
Porosity Modeling

\[ \varepsilon = \frac{V_{\text{void}}}{V_{\text{tot}}} \]
Rock-bed porosity distribution

Porosity: $\varepsilon = \frac{\text{Void volume}}{\text{Total volume of the matrix}}$
Rock-bed porosity distribution

FCC: $\varepsilon = 0.2595$

SC: $\varepsilon = 0.476$

Random packing: $\varepsilon = 0.36 \div 0.43$
Rock-bed porosity distribution
Particles packing – channeling effect

Negligible when: \( \frac{D_{\text{vessel}}}{D_{\text{particle}}} > 40 \)

Particle packing – axial direction


Porous Media Pressure Drop

\[ v = -\frac{K}{\mu} \frac{dp}{dx} \]
• Darcy-Forchheimer equation (Joseph et al., 1982):

\[
\nabla p = -\frac{\mu}{K}\overline{u} - c_F K^{-\frac{1}{2}} \rho \overline{u}
\]

• where \( K \) is the specific permeability, a property of the porous media [m²]
• \( \mu \) is the dynamic viscosity [Pa s]
• \( \overline{u} \) is the seepage velocity [m/s]
• \( c_F \) is a dimensionless form drag parameter which varies with the nature of the porous medium
• \( \rho \) is the fluid density.

\[
K = \frac{D_p^2 \cdot \varepsilon^3}{150 \cdot (1-\varepsilon)^2}
\]

\[
C_F = 2c_F K^{-1/2} = \frac{3.5 \cdot (1-\varepsilon)}{D_p \cdot \varepsilon^3}
\]

Porous Media Heat Transfer Modeling
Porous Media Effective Thermal Conductivity

- Porous Media Energy Equation

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- \( k_{eff} \) is the Effective Thermal Conductivity

\[
k_{eff} = k_{cond} + k_{conv} + k_{rad}
\]
Heat transfer mechanisms:

(1) thermal conduction through solid;

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(5) thermal conduction through the fluid film near the contact surface of two packings;

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6. heat transfer by convection solid-fluid-solid;

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7. heat transfer by advective mixing.

Heat transfer in packed beds

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5. Thermal conduction through the fluid film near the contact surface of two packings;
6. Heat transfer by convection solid-fluid-solid;

Heat transfer contributions 1 to 5 can be accounted for by using an **effective thermal conductivity** for a stagnant fluid.

Accounted for by mass, momentum and energy transport equations.
Radiative contribution to the ETC

Packed bed of alumina spheres of 5 mm diameter and air as heat transfer fluid.

\[ k_{eff} = k_g \left[ \varepsilon \left( 1 + \frac{\beta h_{rv} D_p}{k_g} \right) + \frac{\beta (1 - \varepsilon)}{\alpha} \right] \]

CFD model validation
First lab-scale prototype (Biasca – TI)

Prototype thermal capacity = 6.5 MWh_{th}
CFD model potential
Industrial-scale TES unit

Characteristics:
- thermal capacity = 1 GWh\textsubscript{th};
- upper diameter = 25.7 m;
- lower diameter = 21.7 m;
- rock-bed height = 9.5 m;
- rocks diameter = 0.03 m;
- HTF = air.
- **Initial condition** (\( t = 0 \) sec):
  - TES unit at dead-state (\( T = 17^{\circ}C \))

- **Charge phase**:
  - duration: 12 hrs
  - \( T_{\text{charge}} = 650^{\circ}C \)
  - HTF mfr = 89.6 kg/sec

- **Discharge phase**:
  - duration: 12 hrs
  - \( T_{\text{charge}} = 270^{\circ}C \)
  - HTF mfr = 89.6 kg/sec
CFD simulation results – 30 consecutive cycles
Sensible + Latent Heat Storage
A possible solution: combined sensible and latent TES

Sensible heat TES:
- reliable and most exploited solution to store thermal energy;
- possibility of using a low-cost filler material as storage medium;
- drop of outflow air temperature towards the end of discharge.
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Latent heat TES:
- PCMs can store and release thermal energy at constant temperature;
- relatively low thermal conductivity;
- economically unfavourable.

Combine the two concepts in a way that exploits the benefits of both while alleviating the critical issues.
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Combined sensible and latent TES

Charging Discharging

PCM Latent TES

Rock bed Sensible TES
Combined sensible and latent TES Prototype

Prototype thermal capacity = 42.4 kWh$_{th}$

G. Zanganeh et al., *Stabilization of the outflow temperature of a packed-bed thermal energy storage by combining rocks with phase change materials*, Applied Thermal Engineering, 70:31-320, 2014
Combined sensible and latent TES Prototype

PCM: AlSi$_{12}$ encapsulated in steel tubes
TES filler: natural rocks

G. Zanganeh et al., *Stabilization of the outflow temperature of a packed-bed thermal energy storage by combining rocks with phase change materials*, Applied Thermal Engineering, 70:31-320, 2014
Combined TES: monodimensional modeling approach

\[
(1 - \phi_{\text{epcm}}) \frac{\partial (\rho_g e_g)}{\partial t} + (1 - \phi_{\text{epcm}}) \frac{\partial (u \rho_g h_g)}{\partial x} = a_w h_{\text{w,conv}}(T_w - T_g) + q_{\text{enc,g}}
\]

\[
\phi_{\text{enc}} \frac{\partial (\rho_{\text{enc}} e_{\text{enc}})}{\partial t} = -q_{\text{enc,g}} + q_{\text{cond,enc}} + q_{\text{rad,enc}}
\]

\[
+ \frac{a_w f_{\text{cont, w}} e_{\text{enc}}}{(r_{\text{tank}} - r_{\text{enc}}) \ln \left( \frac{r_{\text{tank}}}{r_{\text{tank}} - r_{\text{enc}}} \right)} (T_w - T_{\text{enc}}) + q_{\text{pcm, enc}}
\]

\[
(1 - \phi_s) \frac{\partial (\rho_g e_g)}{\partial t} + (1 - \phi_s) \frac{\partial (u \rho_g h_g)}{\partial x} = h_v (T_s - T_g) + a_w h_{\text{w, conv}}(T_w - T_g)
\]

\[
\phi_s \frac{\partial (\rho_s e_s)}{\partial t} = \frac{\partial}{\partial x} \left( k_{\text{eff}} \frac{\partial T_s}{\partial x} \right) + h_v (T_g - T_s)
\]

\[
+ a_w h_{\text{w, cond-rad}}(T_w - T_s)
\]
1D Simulations vs Experimental data

- PCM temperature along the centerline as function of number of cycles or non-dimensional time during cycling.

1D Simulations vs Experimental data

- Centerline and wall temperatures as a function of position during discharging.
- Temperature distribution after charging at 1.67 h, 2.22 h, 2.78 h.

a) 1.67 h; b) 2.22 h; c) 2.78 h.
- Velocity magnitude at 1.67 h after charge start.
- Temperature at 1.67 h after charge start.
CFD Simulations vs Experiments

- Temperature distribution in the charge phase

![Diagram showing temperature distribution over non-dimensional time]
Ongoing and future research activities
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- PCM region:
  - Modeling encapsulation effects
  - Heat exchange coefficient definition
  - Tubes arrangement effects.

- TES studies:
  - Analyse the thermo-fluid dynamics of a TES system operating under high-pressure condition (AA-CAES)
  - Simulate Pollegio TES system:
Pollegio experimental plant

- Pollegio (Valle Leventina)
- ALACAES
- Alptransit service tunnel
Pollegio experimental plant
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  - Modeling encapsulation effects
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- TES studies:
  - Analyse the thermo-fluid dynamics of a TES system operating under high-pressure condition (AA-CAES)
  - Simulate Pollegio TES system
  - Analyze experimental data of the Pollegio plant (available by the end of the year).
Thank you for your attention!