Methodology development for accelerated generation of thermal energy storage models for transient system simulations

Towards more efficient modeling and simulation of large-scale hot-water underground pit and tank TES

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OVERALL AIM: Accelerated generation of new TES models

WHY?
# Modeling process: Complex, time-consuming and costly
# New emerging TES technologies and more complex energy systems → Multi-annual dynamic system simulations are necessary for proper design, integration and market launch of these new technologies

General procedures, guidelines & modeling toolboxes

Large-scale TES

Development

Validation

Application & testing

Thermochemical TES

Open-source
Equation-based, object-oriented and hierarchical
High reusability, flexibility and expandability

Source: Anton Sauermilch
Modeling and simulation of LTES: Motivation

Why large-scale hot-water underground tank and pit TES? [1]

- Seasonal and short-term storage of renewable energy
- Provision of peak load capabilities for power grids (Power2Heat) → Sector Coupling
- “Potentially cheapest way to store thermal energy”
- Attractive integration in urban environment possible (“no free-standing, high structures”)
- …
- Central element of future district and local energy system in order to increase the share of volatile renewable energy sources

Why system simulations?

- Increased no. of components and complexity of future systems
- Long-term (multi-annual) investigations are necessary
- Experiments practically limited to the component level
- In general: for parameter studies, techno-economic analyses, ecological analyses, … → System simulations are necessary in order to fully exploit the potential of LTES technologies

Why a new Modelica model? (Why no Co-simulation)?

- To fully exploit the features of Modelica (e.g. flexibility, expandability,…)
- Co-simulation may lead to [3]:
  - long implementation time,
  - poor computational performance and loss of information.

Why Modelica? [2]

- High reusability, flexibility and expandability
- Faster modeling process than other modeling tools (e.g. TRNSYS)
- Open-source → very large no. of available libraries from different domains (multi-domain modeling)

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Model description: Overview

- Modelica model, developed and simulated within the modeling and simulation environment Dymola [4]
- Based on existing models from the Modelica Standard library [5] and the Modelica Buildings library [6], supplemented by several adaptions and extensions of these models
- Two main models: fluid domain model and soil domain model

Model description: Fluid domain model

- Fluid domain model: 1D multi-node approach
  - Fluid domain is divided into finite-volumes (nodes) with a uniform horizontal temperature
  - Governing equations:

\[
\dot{m}c_w T_{\text{out}}(t) = k_i A_c (T_{i+1}(t) - T_i(t)) \frac{z_{i+1} - z_i}{z_i - z_{i-1}} + \dot{m}c_w(T_i(t)) + U A_i (T_i(t) - T_\infty)
\]

**Model description: Soil domain model**

- **Governing differential equation:**

  Two-dimensional transient heat conduction in cylindrical coordinates with constant thermophysical properties [8]:

  \[
  \frac{1}{\alpha} \frac{\partial T(r,z,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T(r,z,t)}{\partial r} \right) + \frac{\partial^2 T(r,z,t)}{\partial^2 z}
  \]

  where \( \alpha = k/(\rho \cdot c_p) \) is the thermal diffusivity of the soil with the thermal conductivity \( k \), the density \( \rho \) and the specific heat capacity \( c_p \). \( T \) is the temperature of the node at the time \( t \), the radial location \( r \) and axial location \( z \).

- **The differential equation is solved using the finite difference method (FDM) and by proper discretization of the soil domain.**

Presented model configuration was examined in a validation case study:

- Comparison of the simulation results against measurement data of a real Danish PTES (in Dronninglund)
- The Modelica model was evaluated as a stand-alone component and all other system components were excluded from the validation
- Hourly temperature and mass flow rates at the corresponding inlet and outlet diffusers were used as input data for the simulation
- Major model parameters (e.g. cylinder dimensions, U-values, diffuser heights) were adapted to the truncated pyramid geometry

Comparison between simulated and measured storage temperatures for the year 2015 in daily resolution; a) at the three inlet and outlet diffuser heights; and b) at the top, between top and middle and middle and bottom diffuser.

$R^2$ values are presented in the corresponding colored boxes.
Validation case study: Results (2) and conclusion

Comparison between measurement data and simulation results for the validation year 2015. Measurements derived from [10] and [11].

<table>
<thead>
<tr>
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<th>Meas.</th>
<th>Sim.</th>
<th>Difference</th>
<th>[%]</th>
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<td></td>
<td>[MWh]</td>
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<td>Discharged energy</td>
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<td>1 124</td>
<td>-151</td>
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<tr>
<td>Top</td>
<td>788</td>
<td>827</td>
<td>39</td>
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<td>Side</td>
<td>-</td>
<td>256</td>
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<tr>
<td>Bottom</td>
<td>-</td>
<td>42</td>
<td>-</td>
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<td>Storage efficiency [%]</td>
<td>90.0</td>
<td>91.1</td>
<td>1.1</td>
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</tbody>
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**Conclusion of validation case study:**

- The model provides satisfying results for the application in system simulations → small deviations in charged & discharged energy and storage temperatures
- Somewhat higher deviations in thermal losses (especially side and bottom thermal losses) → this has to be considered for detailed design studies
- Possible reasons for the deviation in thermal losses:
  - Parameterization of the model
  - Deviations in the geometry

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Further investigations and applications of the model (so far)

- Cross-comparison against other numerical models (TRNSYS and COMSOL Multiphysics) with same validation case study (PTES Dronninglund)
  → Good agreement with comparable models suited for system simulations (see [12])

- Comprehensive model comparison together with other LTES models of different simulation tools (COMSOL Multiphysics, TRNSYS and MATLAB/Simulink) in a generic case study
  → Good agreement between the developed model and all other models (see [13])

- Application of the model within the project giga_TES for system simulations, techno-economic analyses and parameter studies of several case studies of different locations and scenarios in Vienna and Salzburg (Austria)
  → Model showed a good compromise between computational performance and accuracy (see [14])


Conclusion and outlook

**Conclusion**

1. Hot-water underground LTES can massively increase the proportion of renewable energy in future local and district energy systems.
2. To fully exploit the potential, comprehensive planning and tuning of the overall system by dynamic system simulations is necessary.
3. Modelica-based simulation tools show many advantages over other established tools.
4. Consequently, a novel Modelica LTES model was developed.
5. The validation case study and further investigations showed an adequate accuracy and a good usability of the model for system simulations.

**Outlook**

- Extension of the storage model to conical geometries is in progress
  - Preliminary results of the validation case study and the cross-comparison with other numerical models show promising results (*should hopefully be published in another paper soon*)
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