Developments in simulation and evaluation of large-scale hot water tanks and pits in renewables-based district heating

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Abstract
Large-scale thermal energy storages (TES) are advantageous to bridge the seasonal gap between heat demand and availability of renewables. Yet, the high investment costs associated with large-scale TES is still seen as a major barrier. Challenges are space availability and the presence of groundwater. The complexity of the processes and interactions motivate the application of simulation tools for planning such systems. This work summarizes the features of the different TES models, develops numerical models in different tools and compares the results with respect to thermal losses and temperature stratification.

Key Innovations
- Development of large-scale TES models in several tools to address the relevant planning questions.
- Cross-comparison of the models against validated reference model.
- Establishment of data for cross-validation of future models.

Introduction
Due to the increasing necessity for measures in energy efficiency, it is urgent to transfer cities into more energy-efficient ones with a focus on both energy systems and buildings stock. In this context, the heating and cooling sector significantly contributes to the total energy demand in the European Union (EU) with a share of around 50% out of which a major fraction of 75% is still met by purely conventional fuels with almost 50% via combustion of natural gas. Whilst the remainder is supplied from low-carbon energy sources. In this context, a share of 11% is provided by biomass resources and another portion of 7% is supplied utilizing nuclear energy. Whereas the remainder share 7% of the EU heating and cooling comes from renewable energy sources. Thus, a main challenge is the decarbonization of this sector, which is strongly reliant on the conventional fuels (Ochs, F. et al., 2019).

The buildings sector represents one of the major energy consumers in the EU and it accounts for more than of 40% of the total energy demand whereby a major contribution is attributed to the heating and cooling activities. Therefore, measures for energy efficiency are introduced to promote the buildings stock. As a result, the heating and cooling sector shows promising potential for renewables integration leading to systematically phase-out the fossil fuels and thus to decarbonization. Yet, the main disadvantage of the renewables is their intermittency (Brunner, C. et al., 2020). Hence, thermal energy storage emerges as a key player due to its capability of capturing thermal energy for later use, bridging the gap between energy demand and supply and further facilitating sector-coupling (Fridgen, G. et al., 2020).

To exploit locally available renewables (e.g. geothermal), or sources (e.g. waste heat) (Baidya, D. et al., 2020), the renewables-based district heating (R-DH) is a crucial concept. Thus, it becomes more significant to scale the TES up to large volumes to fulfill the district tasks and to provide heat whenever needed. This is attributed to the fact that such TES is capable for storing thermal energy for lengthy periods up to several months. Besides, the increase in the TES volume induces a notable reduction in the thermal losses due to the good surface area-to-volume ratio (SA/V). Further, the larger the TES volume is, the cheaper the specific cost (€/m³) under same structural and construction conditions.

The most promising types of seasonal TES are favorably installed underground. Literature classifies the most common types of STES into: 1) aquifer TES (ATES), 2) borehole TES (BTES), 3) tank TES (TTES) and 4) pit TES (PTES). It is important to highlight that ATES and BTES operate with low temperature and moderate flowrates and, therefore, moderate charging/discharging energy rates. Whereas TTES and PTES are known for achieving high charging/discharging energy rates.

Figure 1 shows that the planning and construction of large-scale TES is a complex process whereby several variables (e.g. location, hydrogeological conditions, construction type, size, geometry, cost, safety and environmental issues) have to be considered. Consequently, research studies employed simulations for planning assessment to address the impact of these variables (Narula, K. et al., 2019).

Real experiments are also essential to inspect the impact of these variables and quantify their magnitude to address the most relevant parameters. Yet, it is hardly feasible to construct pilot TES projects with large-scale volumes for experiments due to the high capital cost. Besides, another risk is the potential of low TES performance. Therefore, calibrated STES and system simulations found their place favorably to examine the planning and operation of large-scale systems (Narula, K. et al., 2019).
Advances in simulations of large-scale TES

The interconnections among the different categories shown in Figure 1 highlight the importance of TES simulations. Besides, the construction of large-scale TES systems tends to be costly and, therefore, this inevitably demonstrates the significance of TES modeling to guarantee the economic feasibility and the effective planning layout for the system. As a result, modeling process suits ideally to these tasks and helps in understanding the operation of these systems, which permits in producing the optimal planning and later developing them. Consequently, it is remarkable that TES modeling can be categorized into a wide range of levels following the goal of the investigation. Hence, TES modeling undergoes a systematic process in which the goals are pre-design, detailed design, technology integration, evaluation and optimization (Dahash, A et al., 2020a).

Figure 2 reveals the TES modeling process hierarchy whereby at the early phase of TES construction a pre-design tool is often used for the planning phase and, then, details are consecutively included in the model until it reaches a detailed model. Next, the TES undergoes a technology investigation as it is integrated within an energy system (e.g. R-DH system). Accordingly, the TES technology is thoroughly evaluated and the outputs are post-processed producing some optimization proposals (e.g. optimal construction type, optimum TES geometry and optimal insulation thickness). Meanwhile, there exist three factors strongly influencing the computation time: level of detail (pre-design, detailed), number of components (technology integration) and simulation timestep (daily, multi annual). These players might substantially affect the computation time as shown in Figure 3. In order to optimally select the right level, the aim of analysis should be beforehand defined (Dahash, A et al., 2020b).

For the pre-design level, some prototyping tools are used to give a glimpse in the TES and its integration and these tools produce preliminary performance indicators. Out of these tools, an online solar district heating (SDH) tool can be used for the preliminary cost-benefit analysis. This tool supports both centralized and decentralized SDH systems. Another pre-design tool is known as “Load Profile Generator”, which is developed using Microsoft Excel. It is a simple monthly-balance tool that simulates TES with a 3-node model neglecting thermal losses to the environment.

Given the complexity seen when modeling DH system and the thermo-hydraulic behavior of large-scale TES (stratification, buoyancy, etc.), a wide range of tools is commonly employed in modeling DH and TES systems. Such tools are commonly categorized into three types:

(a) energy system simulation (ESS) that involves tools like Modelica/Dymola, TRNSYS, Matlab/Simulink;
(b) building physics envelope heat and mass transfer tools such as WUFI Pro and Delphin;
(c) computational fluid dynamics (CFD) such as ANSYS Fluent and CFX; and
(d) multiphysics tools such as COMSOL Multiphysics® (which is also used for building envelope heat and mass transfer).

Consequently, different discretization schemes are employed in simulation tools. Herein, the discretization of the spatial domain is executed using either finite element method (FEM), finite difference method (FDM) or finite volume method (FVM). Besides, the level of detail profoundly depends on the model’s dimensionality. For instance, highly-detailed models require 3-D representation and as the level of detail becomes less important, then the models can be reduced to 1-D models.

ESS tools (e.g. TRNSYS, Modelica/Dymola) often employ FDM as discretization fashion for models represented as 0-D or 1-D. Yet, it is possible to develop 2-D models in such tools but the computation time might exceed the limits. On the other hand, CFD tools (e.g. ANSYS Fluent) require exact representation for the investigated case and, thus, 2-D or 3-D representation become more important.
In order to carry out accurate CFD simulations, the numerical models are often discretized in FVM or FEM fashion. Further, heat transfer applications require accurate domain representation and the utilization of FEM. For example, the TES surrounding soil can be developed in COMSOL Multiphysics as an axisymmetric 2-D model that is discretized in a FEM fashion.

By virtue of CFD, (Panthalookaran et al., 2008) developed numerical CFD models ideally suited for specific tasks (i.e. charging/discharging modes). The models were calibrated against measured data from two buried TES tanks in Germany.

In TRNSYS via FDM, (Bai et al., 2020) developed a model for an underground 3000 m³ water pit located in China. The model was later validated against measured data revealing a good agreement. Yet, such model is applicable for TES with volumes of several thousand with a certain operation scheme. The model can be categorized under the technology integration level.

In an attempt to condense the model complexity, (van der Heijde et al., 2019) utilized time aggregation algorithms (i.e. representative days) to represent an S-DH system equipped with a seasonal TES. It was revealed that the algorithm is computationally cheaper by 10-30 times when compared to simulations without aggregation. Yet, it was concluded that the minimum required number of representative days was not obtained.

Furthermore, (Sorknæs, 2018) developed a simulation method that is capable enough to capture the dynamics of PTES coupled with a heat pump in a S-DH system. The method was tested by comparing the simulated results against the measured data from Drønninglund pit TES for the year 2015. Accordingly, the simulated thermal losses were around 1741 MWh, whereas the measured thermal losses were 1275 MWh. This discrepancy (approx. 35 %) highlights the inaccuracy of this method, which might later lead to wrong conclusions during STES planning phase. The developed model can be classified under the pre-design category.

In this context, the authors developed TES numerical models in several tools in order to allow the examination of different levels of design, planning and integration of large-scale TES systems. The importance of this is each of these models is appropriate for a different level of planning. Hence, a numerical TES model is developed in Matlab/Simulink as a code. While it is implemented as a numerical multiphysics model in COMSOL Multiphysics. The TES model in Modelica/Dymola is the base class model of “stratified” model under Modelica Buildings library (Wetter et al., 2013), but the authors developed this model further for representation of large-scale TES. The model implemented in COMSOL represents high level of complexity, whereas the one implemented in Matlab/Simulink acquires a lower number of equations and, accordingly, less complex. The importance for establishment of different model is attributed to the different levels of the design process as highlighted in Figure 2. Further, Figure 4 illustrates the
allocation of the developed models to the different modeling levels given the maturity of the tools.

In Figure 4, it is clearly seen that COMSOL TES model is appropriate for the detailed design considering TES and surroundings, while it covers the pre-design level of system simulation.

Figure 4: Allocation of developed TES models to the corresponding modelling level.

For Matlab/Simulink TES model, it can capture the detailed design of TES and covers both of system and surroundings levels. As for Modelica TES model, it can encompass the detailed TES with detailed system simulations, whereas the simulations are limited in the surrounding level (e.g. groundwater). In addition, COMSOL Multiphysics supports the co-simulation with Simulink via “LiveLink for Simulink”, which gives the opportunity for advanced system simulations. Out of the developed models, Matlab/Simulink TES model has relatively shorter simulations times. In this regard, it must be pointed out that if groundwater flow is given in the surroundings, then COMSOL Multiphysics is the tool that can fully emulate that amongst the others. Yet, this work does not consider any groundwater flow in the investigated cases. Table 1 reports the allocation of the different tools to the aforementioned design categories. Besides, Table 1 documents the discretization of the models.

Table 1: Allocation of the considered tools to the categories in modelling process hierarchy.

<table>
<thead>
<tr>
<th></th>
<th>COMSOL Multiphysics</th>
<th>Modelica/Dymola</th>
<th>Matlab/Simulink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-design TES</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pre-design System</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Detailed design TES</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Technology integration</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Spatial discretization</td>
<td>FEM</td>
<td>FDM</td>
<td>FDM (TES) and FEM (soil)</td>
</tr>
</tbody>
</table>

Methodology

Development of hot-water TES models

The conceptual TES model is developed in the four different tools to represent axisymmetric geometries (i.e. tanks and pits) and, accordingly, this implies that it is enough to model a single half of the TES in 2D.

The TES fluid domain is developed as a multiport model in which the height of the ports can be specified and discretized into a number \(n\) of segments that are considered with equal volumes rather than equal distances (i.e. equidistant heights). For each segment \(i\), conductive and mass-bound convective heat transfer mechanisms are considered in an energy balance expressed as a partial differential equation as follows:

\[
\frac{\rho A_i c_p}{\partial t} \frac{\partial T_i(t)}{\partial t} = -\left( \rho w c_w \frac{\partial T_i(t)}{\partial z_i} + A_i \frac{\partial}{\partial z_i} \left( \lambda_w \frac{\partial T_i(t)}{\partial z_i} \right) \right) \bigg|_{\text{loss}_i} \quad (1)
\]

\[
\text{\(\text{loss}_i = U_{\text{side}} \cdot P_i \cdot (T_i(t) - T_{\text{g},t}(t))\)} \quad (2)
\]

Where \(\rho\), \(c_p\) and \(\lambda_w\) represent the density, specific heat capacity and thermal conductivity of the storage medium, respectively. Whereas \(A_i\) is the cross-section area of the segment \(i\). Equation (2) expresses the thermal losses from the corresponding segment \(i\) to the surroundings and, therein, \(U_{\text{side}}\) stands for the overall heat transfer coefficient (HTC) of the TES envelope (fluid to ground). Whilst \(P_i\) is the segment perimeter.

To tackle the buoyancy-driven natural convection, water thermal conductivity encompasses the nominal value and an effective value to enhance the thermal conductivity; consequently, eliminate inverse thermocline. Accordingly:

\[
\lambda_w \text{eff} = \begin{cases} 
\lambda_w & \text{if } \dot{V}_w \neq 0 \\
\lambda_w + C \cdot \left( \frac{\partial T_i(t)}{\partial z_i} \right)^k & \text{if } \frac{\partial T_i(t)}{\partial z_i} < 0 
\end{cases} \quad (3)
\]

The term \(C \cdot \left( \frac{\partial T_i(t)}{\partial z_i} \right)^k\) represents the enhanced thermal conductivity that is theoretically originated from Nusselt and Rayleigh numbers and modified following the given application (large-scale TES). Where \(C\) denotes a constant that brings different dimensional parameters (e.g. volume, height) together with thermo-physical properties (e.g. density, specific heat capacity). The exponent \(k\) is tuned following the application; however, in this case \(k = 0.5\). Moreover, the heat transfer also occurs in the ground and it is described as follows:

\[
\left( \rho g c_{p,\text{g}} \right) \frac{\partial T_{\text{g},i}(t)}{\partial t} = \nabla \cdot \dot{q} \quad (4)
\]

One major shortage of axisymmetric models is the challenge to include the unsymmetrical flow of groundwater, which will eventually violate the symmetry constraints. Hence, 3-D numerical models arise as a quintessential option and, accordingly, COMSOL Multiphysics is the perfectly-suited tool for such investigations.

Furthermore, COMSOL Multiphysics allows the inclusion of multi-physical phenomena (e.g. heat transfer, fluid flow, mass transfer) and permits a spatial discretization in a FE fashion, whereas the models (e.g. TES and surroundings) in Modelica/Dymola are spatially discretized via FDM. The TES fluid domain in Matlab/Simulink is developed as an FD model that is...
coupled with FE ground models.

In addition, it must be pointed out that there is a wide range of option to represent the buried TES with the surroundings. For instance, Figure 6 shows two variants in which (a) represents development of TES with a physical lid, whilst (b) shows a TES model developed with a lid resistance. The major difference between both options can be highlighted with the influence of heat capacity and heat transfer path. As option (a) has a physical lid, then the lid can store the heat and play the role of a thermal damper. Option (b), on the other hand, lacks to the lid capacity and, therefore, the resistance should be furthered extended in order to: 1) prevent the thermal bridge effect that might appear, and 2) emulate the lid capacity.

COMSOL Multiphysics TES model adopts option (a), whereas option (b) is apparent for the numerical TES model developed in Matlab/Simulink. Whilst the TES model in Modelica is a combination of both as it takes advantage of the resistance from option (b) and the capacity from option (a). Furthermore, these options might lead to a difference in the TES installation depth depending on the thickness and installation of the lid (e.g. above ground or underground).

**Operation scenario, boundary conditions and assumptions**

In this work, the aim is to develop numerical models that are suitable for the different levels of the modeling process. Therefore, the simulation boundaries are restricted to the TES component in order to easily locate the models’ faults. Therefore, system simulations are excluded at this stage and, consequently, no R-DH system is simulated.

Yet, the R-DH operation plays an important role in the charging/discharging phases of the TES component. Thus, the load profile generator tool is utilized to simulate a district with 833 highly efficient buildings each with ~2 kW. Next, the excel-based tool incorporated a heat source with a constant power (e.g. industrial waste heat, geothermal) of 1.5 MW as shown in Figure 7. Then, the excel-based tool included an adiabatic TES component (i.e. no losses).

Consequently, the charging and discharging flowrates were defined starting from the load curve and the heat source curve. In particular, during the charging phase, the available energy from the heat source is used to satisfy the summer load and the remainder is stored in the TES. While during the discharging phase, the available energy from the heat source is used to satisfy part of the winter load, then the required remaining power is extracted from the TES. Thus:

\[ Q_{ch/dis} = \frac{Q_{source}(t) - Q_{load}(t)}{\rho \cdot c_p \cdot \Delta T} \]  

Accordingly, time-series inputs are used for the temperature and flowrate on both inlet/outlet ports of the examined TES component. Figure 8 and Figure 9 show the hourly profiles of flowrate and corresponding temperature input used for the TES operation. Note that the positive flowrate stands for the charging phase, whereas the negative one represents the discharging. Besides, the work assumes a constant R-DH supply temperature of 90°C and a return temperature of 60°C. For the comparison of the models, an underground
(buried) tank with a volume of 100,000 m³ and a height of 25 m is used. The tank is initialized with a temperature of 10°C, which is equivalent to the ground initial temperature.

Given the fact that the TES insulation level (on the top, sidewalls and bottom) plays an essential role in the techno-economic performance of the TES, it becomes crucial to examine the TES under several insulation cases. Accordingly, the comparison cases are categorized into two primary items: “non-insulated” and “insulated”. Each major item is subdivided into three minor cases considering different values for the insulation of the lid (TES cover). In this regard, the non-insulated cases are labelled with (Case 1), whereas the insulated cases are assigned to (Case 2). Table 2 documents the specifications of the examined cases in this work.

Table 2: Summary of the primary and secondary cases considered in the cross-comparison (Ochs, F. et al., 2019).

<table>
<thead>
<tr>
<th>Case</th>
<th>( U_{\text{top}} ) [W/(m².K)]</th>
<th>( U_{\text{side}} = U_{\text{bot}} ) [W/(m².K)]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a 0.05</td>
<td>90</td>
<td>Non-insulated</td>
</tr>
<tr>
<td></td>
<td>b 0.1</td>
<td>90</td>
<td>Non-insulated</td>
</tr>
<tr>
<td></td>
<td>c 0.15</td>
<td>90</td>
<td>Non-insulated</td>
</tr>
<tr>
<td>2</td>
<td>a 0.05</td>
<td>0.3</td>
<td>Highly insulated</td>
</tr>
<tr>
<td></td>
<td>b 0.1</td>
<td>0.3</td>
<td>Moderately insulated</td>
</tr>
<tr>
<td></td>
<td>c 0.15</td>
<td>0.3</td>
<td>Poorly insulated</td>
</tr>
</tbody>
</table>

Simulations setup and preconditioning
(Ochs, F. et al., 2019) pointed out that the large-scale buried TES has low efficiency in the initial operation phase, which lasts from 3 years up to 5 years depending on the insulation level and quality. This is attributed to the fact that this phase preheats the ground until it reaches a thermal equilibrium. Therefore, the cases 1 (non-insulated) should run for 10 years, whilst cases 2 (insulated) run for 5 years. Each simulation year has 365 days (no leap year, 8760 hours). The analysis should be always based on the last year results.

Figure 8 depicts that the TES starts the operational year with a discharging phase and due to the fact that the TES is initialized with a temperature of 10°C, the TES is not capable to provide any useful energy to the R-DH network. Thus, the simulations start on April 20\(^{th}\) (beginning of charging phase) and carry on until the end of the examined case. Accordingly, the simulation start time is set to 9,417,600 [sec] as it represents the 20\(^{th}\) of April of the first simulation year.

Results and Discussion

For the simulations, an hourly timestep is used to carry out the simulations considering the flowrate and temperature as inputs. Furthermore, the developed model in COMSOL Multiphysics will serve as the reference model for the comparison as this numerical was validated against measured data from a large-scale pit TES as reported in (Dahash, A. et al., 2020b). Moreover, to evaluate the deviation in the outcomes, the relative error metric is used as follows:

\[
\epsilon (\%) = 100 \cdot \frac{|Y_j - Y_{\text{ref}}|}{Y_{\text{ref}}} 
\]  

(7)

Where \( Y_j \) and \( Y_{\text{ref}} \) stand for the outcomes of the examined and reference tools, respectively.
Annual operation
Thermal losses
Both Figure 11 and Figure 12 reveal the breakdown of thermal losses for the last year of each examined case. Besides, both figures report the total thermal losses. Figure 11 depicts a good agreement in the total thermal losses for the non-insulated cases at the end of the year (10). It is seen that the top contribution of the thermal losses is comparable for all tools. However, a slight discrepancy is seen in the sidewall and bottom contributions. Besides, the deviation between COMSOL Multiphysics and Modelica is appx. 2 %, whereas a deviation of ε = 1.5 % is notable between COMSOL Multiphysics and Matlab/Simulink.

The discrepancy between the numerical models remarkably decreases (ε < 1 %) for the insulated cases as displayed in Figure 12 due to less amount of thermal losses is transferred to the ground. In this regard, the ground discretization plays a role in the calculations, particularly when large amount of energy is transferred from TES to ground and, therefore, better ground discretization might be required. In other words, the TES-ground coupling can be improved for the deviating numerical models in order to reduce the discrepancy when no insulation is used. Yet, this leads to significant increase in the computation time.

Despite the fact that the analysis of the insulated cases was carried out for the 5th year, the TES still has better performance than that installed without insulation, which its analysis was based on the 10th year. Therefore, this highlights the role of techno-economic analysis for the planning phase of large-scale TES systems.

Temperature profile
The temperature profile at selected relative heights is compared for the different tools. The relative height is expressed as follows:

\[ h^* = \frac{h}{h_{TES}} \]  

Figure 13 exhibits the temperature profiles at selected relative heights of the TES (0.05, 0.1, 0.25, 0.5, 0.75, 0.9 and 0.95). Therein, a remarkable matching is revealed among the examined tools in terms of TES stratification development. Besides, all models are capable to capture the dynamic behavior. Yet, a discrepancy between COMSOL numerical model and the other models is clearly noticed for the rapid temperature increase or decrease. This is attributed to the fact that the TES and its surroundings are developed as a multiphysical model with FE discretization and advanced numerical solvers that allow to perform accurate computations in COMSOL Multiphysics.
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Table 3: Average computation time for the tools considered.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMSOL Multiphysics</td>
<td>142 min</td>
<td>121 min</td>
</tr>
<tr>
<td>Matlab/Simulink</td>
<td>6 min</td>
<td>3 min</td>
</tr>
<tr>
<td>Modelica/Dymola</td>
<td>37 min</td>
<td>23 min</td>
</tr>
</tbody>
</table>

Conclusions

The work presented a methodology to develop numerical models for simulation of large-scale thermal energy storage (TES). The proposed approach is reproducible and, thus, different numerical models were implemented in several tools (i.e. COMSOL Multiphysics, Modelica and Matlab/Simulink).

The establishment of the different models was meant to use them in the various levels of the modelling process with an acceptable deviation between the detailed-design and the pre-planning model. Thus, the work conducted a cross-comparison among the models considering two insulation cases. The outcomes indicated a good agreement among all models considering the energy balance contributors and temperature profile. Yet, a deviation was observed for the non-insulated cases. It is important to pinpoint that future work should focus more on the comparison of other aspects such as the TES in a storage phase for a period of 10 years (i.e. TES cooling operation).

Acknowledgments

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat capacity</td>
<td>$W/(m^2.K)$</td>
</tr>
<tr>
<td>$h$</td>
<td>Convective heat transfer coefficient</td>
<td>$J/kg$</td>
</tr>
<tr>
<td>$h^*$</td>
<td>Relative height</td>
<td>-</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flowrate</td>
<td>$kg/s$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat (i.e. thermal energy)</td>
<td>$J$</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat flux</td>
<td>$W/m$</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>$K$</td>
</tr>
<tr>
<td>$t$</td>
<td>Time step</td>
<td>$s$</td>
</tr>
</tbody>
</table>

Figure 13: Temperature profile comparison at selected relative heights of the TES for insulated case 2a at the 5th year.

Yet, it is meaningful to highlight that COMSOL model displays higher temperatures at $h^* = 0.05$, 0.1 and 0.25 compared to other tools. This is due to the fact that COMSOL TES model predicts the bottom thermal losses at lowest compared to all other tools. Accordingly, it deems that the soil model requires further development in other tools to further reduce the minor deviation. Besides, this influence is often ascribed to the small TES height of 25 m for tanks. It is held that if the TES height increases, then there might exist a good potential to develop better stratification profile along TES height (Dahash, A et al., 2020a); consequently, it might be possible to eliminate this slight discrepancy.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>Total heat transfer coefficient</td>
<td>W/(m²·K)</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Volumetric flowrate</td>
<td>m³/s</td>
</tr>
<tr>
<td>$Y$</td>
<td>Simulation output</td>
<td>[-]</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical axis inside the tank</td>
<td>m</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity</td>
<td>W/(m·K)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Relative error</td>
<td>%</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>kg/m³</td>
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</tbody>
</table>

**References**


