Detailed Axial Symmetrical Model of Large-Scale Underground Thermal Energy Storage

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Abstract

Seasonal thermal energy storage (STES) systems are key components for expanding the renewables share in the energy scheme as they offer the dispatchability and flexibility. Therefore, thermal behaviour of such systems is of interest. STES can influence the surroundings causing a violation to the hydro geological standards (e.g. groundwater's temperature exceeding 20°C to 25°C). In this work, an underground tank and pit thermal energy storage (TES) are numerically modelled. The model considers the storage system and the surroundings around the TES. Then, the temperature distribution in the TES and the ground is investigated. In particular, thermal stratification in the TES is examined and, finally, interaction between TES and the surrounding ground is illustrated.

Introduction

Large-scale thermal energy storage (TES) systems are envisioned as an active approach for transition to sustainable energy utilization in many urban centers [1]. TES creates efficient energy solutions by being integrated into district energy systems [2]. Therefore, it offers a potential for renewables expansion in the overall energy scheme. Thereby, seasonal thermal energy storage (STES) represents a powerful practice for providing a local, affordable and low-carbon energy as it helps to bridge the gap between winter heating demand and solar heat availability in summer [3].

Yet, the energetic and exergetic efficiencies of STES are strongly subjected to a number of parameters: TES geometry (e.g. cylindrical or conical), TES type (e.g. tank or pit), operating temperature level, ground conditions (e.g. presence of groundwater), etc. Accordingly, it is often challenging to compare various construction types of STES with maintaining low investment costs [4]. Consequently, research has been ongoing to address modelling of STES. This is also because construction of large-scale TES tends to be costly and, accordingly, the importance of modelling is strongly emphasized as an effective approach to achieve the economic and technical feasibilities.

Further, some boundary conditions can significantly influence STES efficiency. For instance, the groundwater flow might cause an increase in thermal losses and, thus, groundwater temperature exceeds a given temperature causing a violation to some hydro- geological standards. Hence, numerical simulations found its place favorably for such investigations because of its multiphysics approach for providing more accurate and robust solutions. Yet, the authors found that modelling of large-scale TES is poorly investigated in literature. In addition, the literature mentioned the high computation efforts required for modelling of STES.

State of the Art

Thermo-hydraulic modelling in TES has received a great attention in literature in terms of stratification and its influence on system performance, tank design, thermal losses, etc. Nevertheless, such a phenomenon in large-scale tanks and pits has been poorly investigated and its relation directly and/or indirectly with geometry of large-scale TES considering the surroundings (soil, groundwater) is rarely reported in literature.

For instance, Panthalookaran et al. [5] presents numerical CFD models that are validated for charging/discharging modes against monitored data from two buried storage tanks in Germany. One is located in Hannover–Kronsberg with a total volume of 2,750 m^3, whereas the other is the underground TES in Friedrichshafen–Wiggenhausen with a volume of ca. 12,000 m^3. Later, a new characterization method for performance evaluation of various boundary designs during standby mode in large-scale stratified hot water tanks was developed by utilizing these two models [6].

CFD simulation require large computation efforts to provide the solution for partial differential equations and, presently, this is often seen not practical and also in the near future [7]. As a result, assumptions are frequently given for geometry, material properties and boundary conditions in the simulation, which produces a notable reduction of the computation efforts forming the so-called "coarse models" [4]. Yet, this reduction has a cost that yields sometimes a defect in the depiction of thermal hydraulic behaviour and, accordingly, coarse models do not accurately account thermal losses. Still, research has been ongoing reporting coarse models for large-scale TES. For example not limited, Ochs [8] presented a dynamic numerical model based on finite element discretization. The model is able to represent various construction shapes (cylinder, cone) for underground hot water TES in Matlab/Simulink environment. Then, the model is further coupled to a finite difference model for the ground. Nevertheless, Ochs concluded that there are some difficulties observed during the simulations.

Thus, the authors found a gap in numerical modelling of tanks and pits with consideration of surroundings. The importance of this consideration arises from the fact that in several countries in Europe (e.g. Austria) there are several hydro geological standards. These standards state on preventing the groundwater's temperature from exceeding 20°C to 25°C. This increase in temperature is usually seen due to the long standby period and, thus, higher amount of lost heat that increases the temperature. Therefore, numerical modelling approach is important to investigate the thermal behaviour and to quantify the heat lost to the ground.

This paper describes the development of an axial symmetrical model for circular cross-sectional TES systems (i.e. conical pits and cylindrical tanks) with its surrounding environment, which is able to predict the surroundings temperature with low computation efforts. In addition, the paper depicts the temperature profiles in the TES and the ground.

Model Development

Numerical Modelling and Governing Equations

A numerical axial symmetric model is developed using COMSOL Multiphysics 5.3a [9]. The model is discretized in a finite element fashion as shown in Figure 2 . It is noteworthy to mention that the overall model consists of compiling two component-level models. One component-level model is the TES model, which is developed as 1-D model, whereas the other one is an axial symmetrical 2-D model that is used to represent the surroundings.

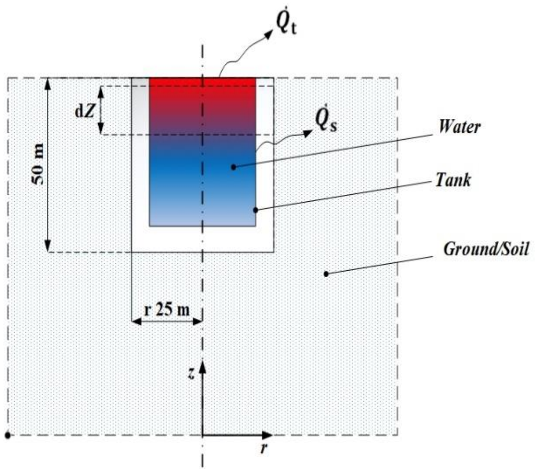

Figure 1. Schematic overview of an underground tank with its surroundings.

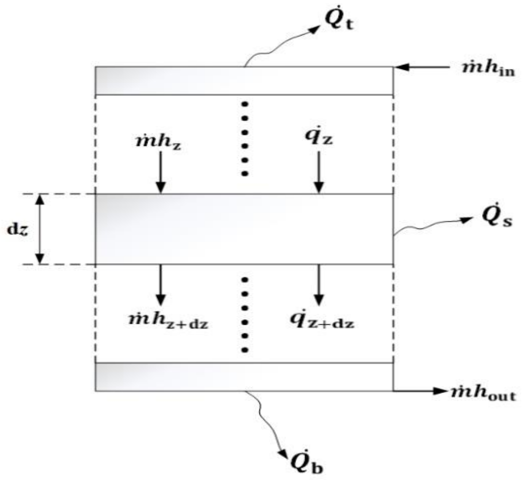

Figure 2. Finite differential element of the underground tank.

The model is suitable only for axial symmetric geometries (e.g. truncated cones or cylinders) for the present time. The impact of the soil and the groundwater on thermal losses from the tank and the stratification can be investigated and, accordingly, the thermal behavior and the water temperatures can be depicted. Thus, the model can provide simulation-based optimizations to determine the optimum distribution of insulation around the TES to minimize the thermal losses. Moreover, the model depicts the temperature of the ground, which helps in return in determining whether regulations (temperature below 20°C to 25°C) are violated.

In the 1-D tank model, the mass of the water flowing in/out the tank is held conserved and, thus, the steady-state continuity equation for the water is given as follows:

$$\dot{m}_{\mathrm{in}} = \dot{m}_{\mathrm{out}} = \dot{m} \tag{1}$$

Whereas the energy stored in a one of the central volume elements can be described by the following equation:

$$\begin{aligned}\frac{\partial E(t)}{\partial t} = \dot{m} \cdot (h_{\mathrm{in}} - h_{\mathrm{out}}) \\ + (\dot{q}_{\mathrm{z}} - \dot{q}_{\mathrm{z+dz}}) \\ - U_{\mathrm{wall}} \\ \cdot A_{\mathrm{side}}\big(T(t) \\ - T_{\mathrm{ground}}(t)\big)\end{aligned} \qquad (2)$$

This equation is implemented using the feature of PDE (partial differential equations) interface in COMSOL Multiphysics:

$$d_{\mathrm{a}} \frac{\partial T(t)}{\partial t} + \nabla \cdot (-c\nabla T) + \beta \cdot \nabla T = f \qquad (3)$$

After rearranging and substituting the damping, mass and diffusion coefficients with their values, the equation becomes:

$$\begin{aligned}(\rho A c_p)\frac{\partial T(t)}{\partial t} = -(\rho A c_p v)\frac{\partial T(t)}{\partial z} \\ + A\nabla \cdot (\lambda_{\mathrm{w}} \nabla T) - U \\ \cdot (\pi d) \cdot (T(t) \\ - T_{\mathrm{ground}}(t))\end{aligned} \qquad (4)$$

Where ρ, c_p and v represent the density, specific heat capacity and velocity of the fluid, respectively. U_{wall} stands for the overall heat transfer coefficient of the storage envelope (fluid to ground), A_{side} is the mantle area of the segment, whereas A is the cross section area of the segment. It is important to mention that when the simulation reaches the upper segment (1st segment in the tank); another heat loss term ($\dot{Q}_{\mathrm{t}}$) is accounted for and, therefore, A_{top} is used to include the upper surface area of the first segment in calculations.

Mesh Generation

The geometry comprises two parts, fluid and soil domains. In this geometry, the insulation is taken as the interface between both domains and, therefore, an overall heat transfer coefficient is selected to represent the heat transfer from the fluid domain to the soil one. A user-controlled mesh structure was preferred for both domains with maximum and minimum element size of 5.43 m and 0.0243 m, respectively.

Simulation Set-up

In order to avoid complex simulations, simplified charging/discharging scenarios were chosen (see Figure 3 and Figure 4) and this allows evaluating the stratification in the TES. During charging, the inlet temperature is set to 90°C, while 60°C during discharging. Table 1 shows a list of parameters used for the simulations.

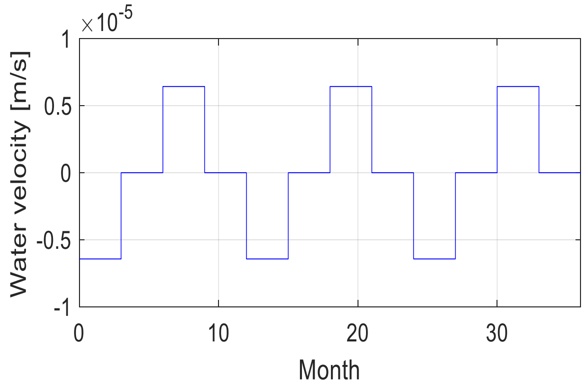

Figure 3. Water inlet velocity over the simulation period (36 months).

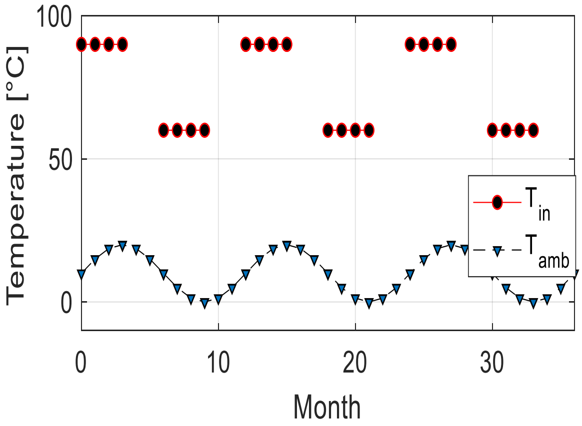

Figure 4. Ambient and water inlet temperatures over the simulation period (36 months).

Results

In the simulation, the investigation period is set to 36 months (3 years) in which one cycle is performed within a year. In addition, a daily time step is selected for storing the results

Figure 5 displays the amount of energy stored in the TES (tank and pit) for the same storage volume. In fact, both curves (blue and red) should have a match since the volume, water properties (specific heat capacity and density), charging/discharging temperatures are the same. Yet, there is a mismatch between them and this can be attributed to different temperature profiles in each case (tank or pit). The more energy seen by the blue line (tank) is due to higher water temperature.

At the beginning of simulations, the TES is assumed to contain initial energy, which means water is stored at 60°C. Then, the energy content starts to increase with time as the charging phase takes place until the

TES is fully charged after 3 months. Next, the energy is stored for 3 months.

It is clearly proven that the tank TES has less heat losses than the pit as seen by Figure 6. This is due to the bigger top area of the pit compared to that of the tank since the hot water gathers at the top. Therefore, the water has lower temperature at the top of the pit compared to the tank and, therefore, the energy content is strongly influenced. Yet, the top thermal losses from the pit is accounted as double as that of the tank as proven by Figure 7. Whereas the bottom losses are smaller compared to that from the tank and this is clearly due to smaller area for pit bottom. Despite the low overall heat transfer coefficient given for the cover of the TES (both cases, 0.1 W/(m^2.K)), the share of the top thermal losses account for more than 20 % of the total thermal losses.

Table 1. Model parameters and its corresponding values and description.

Parameter	**Value**	
	Cylindrical tank	**Conical tank**
Height, H	50 m	50 m
Base diameter, d_b	50.5 m	20 m
Top surface diameter, d_a	50.5 m	75.7 m
Slope angle, α	90	60.9
Volume, V	100 000 m^3	
Water thermal conductivity, λ_w	0.6 W/(m.K)	
Overall cover heat transfer coefficient U_{cover}	0.1 W/(m^2.K)	
Overall wall heat transfer coefficient, U_{wall}	0.3 W/(m^2.K)	
Overall bottom heat transfer coefficient, U_{bottom}	0.3 W/(m^2.K)	
Ground thermal conductivity, λ_g	1.5 W/(m.K)	
Ground specific heat capacity, c_{pg}	880 J/(kg.K)	
Ground density, ρ_g	1000 kg/m^3	

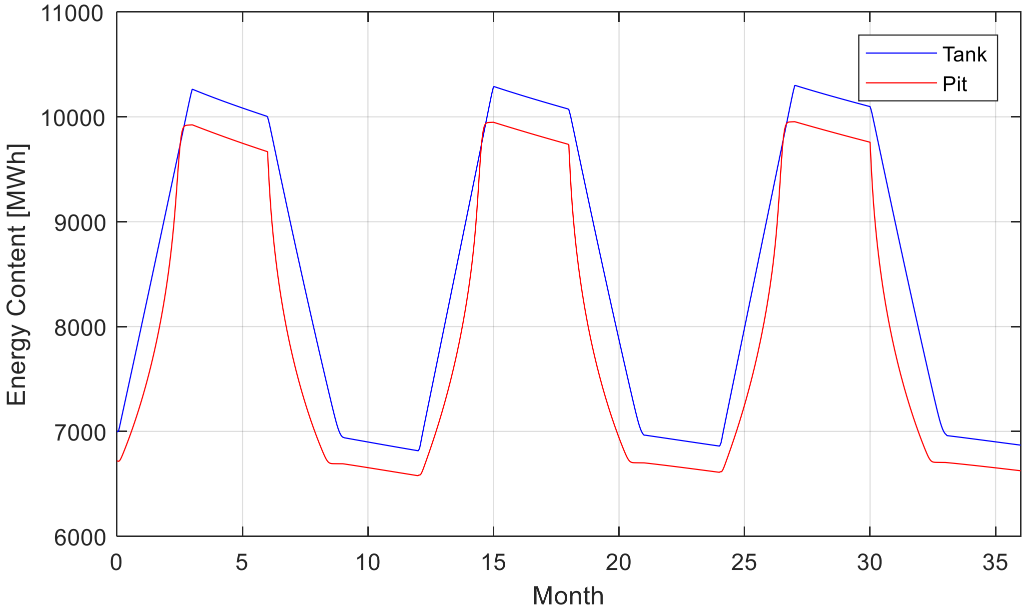

Figure 5. Energy stored in the underground storage over 36 months.

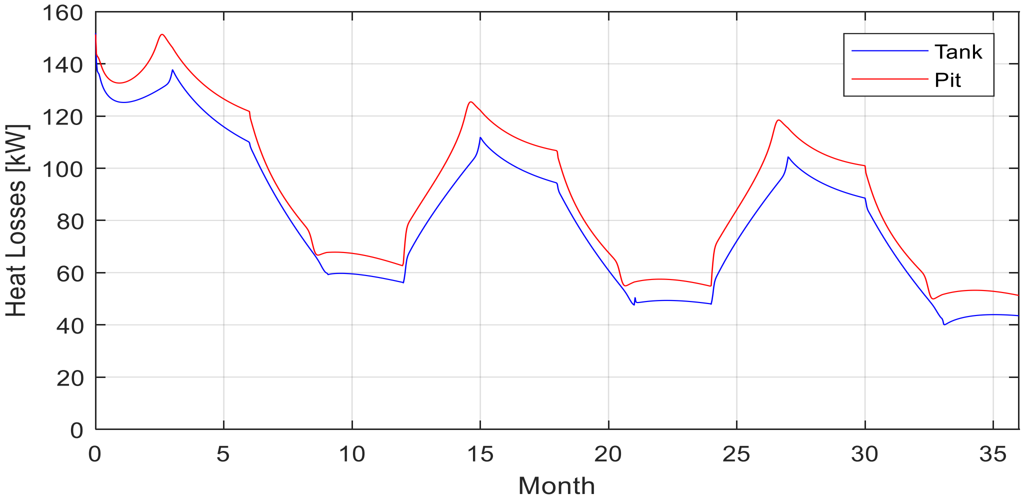

Figure 6. Heat lost from the underground storage over 36 months.

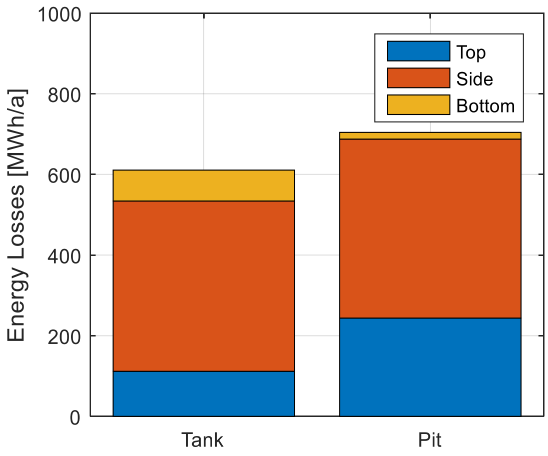

Figure 7. Comparison of energy losses calculated for a constant charging temperature with 90°C and constant discharging temperature of 60°C for a storage volume of 100,000 m^3.

Moreover, it is noteworthy to highlight that the thermal losses decreases over time as seen by Figure 6. The reason behind is that the ground temperature surrounding the TES increases over time as shown in Figure 8 and Figure 9 for the status after three years of operation. Thus, this indicates a high importance for better insulation enclosing the TES in order to prevent the increase in ground temperature.

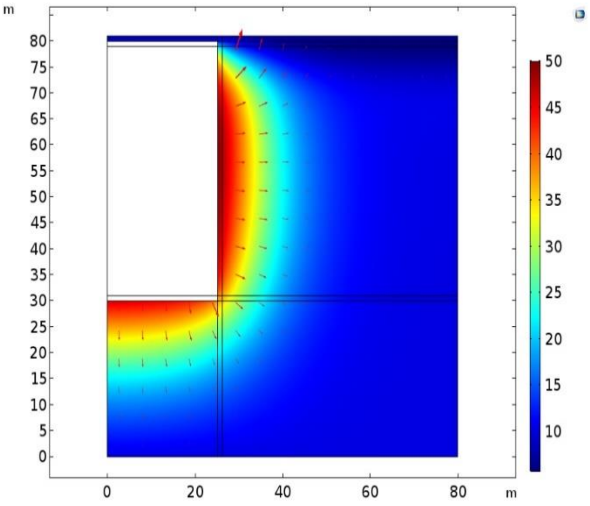

Figure 8. Contour plots for the surroundings of the tank at the end of the 3rd year.

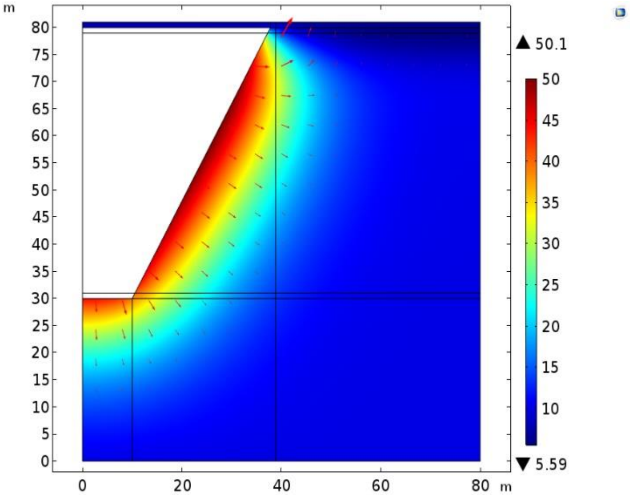

Figure 9. Contour plots for the surroundings of the pit at the end of the 3rd year.

In Figure 10 and Figure 11, the water temperature in the TES is displayed for different time steps starting from a storage in idle mode until the end of the charging mode. The stratification of the storage medium is correctly implemented and at least qualitatively correct. However, in the near future, further validation work is required.

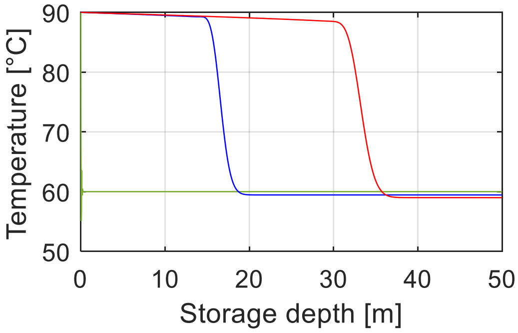

Figure 10. Charging mode in the tank TES.

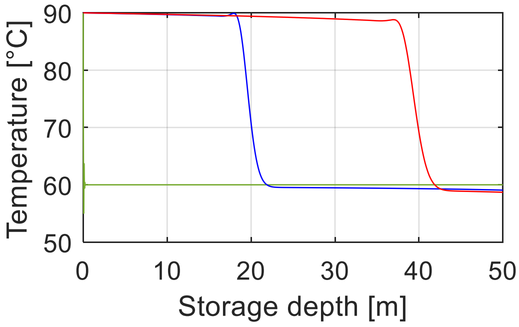

Figure 11: Charging mode in the pit TES.

It is held that both models are good and they can undergo the next phase of development, where the validation takes place. Yet, some issues in regard modelling of pit TES are noticed and need to be overcome. The issues concern mainly the geometry of the pit as it has a slope and, therefore, there is a need to define variable (radius, r) as a function of the pit depth (z). It is found that COMSOL tool delivers inaccurate results during simulation. To overcome such an issue, the radius function has to be defined locally. By other words, this function should be defined under the model section and not globally. Also, it is important to define the angle in the model as a parameter. Otherwise, the tool is not able to identify the radius function.

Conclusion

Large-scale TES systems have attracted a great interest in the recent years to serve as an emerging technology for a wide range of applications, especially for solar-assisted DH applications. Therefore, research has been ongoing to examine and evaluate these systems and set a roadmap for integrating them in district energy systems.

This study presents an axial symmetrical 1-D tank model and an axial symmetrical 2-D ground model. Both models were developed in COMSOL Multiphysics and coupled, then, the models were tested with exemplary charging/discharging profiles (flowrates and temperatures) to inspect the thermal stratification in the tank and the pit, respectively.

The models are also able to examine underground axial symmetric structures (e.g. TES systems with truncated conical or circular geometries) and, therefore, it provides a thermal analysis for such systems, which makes it promising to optimize these structures in terms of reduced thermal losses and investment costs.

The results depict that the thermo-hydraulic behavior of the storage medium is correctly implemented and delivers qualitatively correct results. Validation against measured data is supposed to be done as a next step. Also, the results reveal that the ground is highly influenced during the storage phase in which the surroundings temperature exceeds 40°C (see Figure 8 and Figure 9). Therefore, it is held that an amount of energy is stored in the ground and it is difficult to retain it back. Hence, better insulation system is required to prevent this loss of energy as well as to protect the ground from violating the hydro- geological standards.

Moreover, the models experience low computation time as they simulate an underground TES system over 36 months within a duration of maximum 20 minutes for the tank, whereas it costs 30 minutes for the pit due to more edges and complex boundaries. Yet, the results impose that the models are reliable.

Future works will mainly consider the validation and calibration to test the goodness-of-fit for the models. Additionally, parametrizing the models through LiveLink feature that couples COMSOL Multiphysics with Matlab is a look-forward goal in the next phase of development.

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