DETAILED 3-D MODELS OF A LARGE-SCALE UNDERGROUND THERMAL ENERGY STORAGE WITH CONSIDERATION OF GROUNDWATER CONDITIONS

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SUMMARY

Seasonal thermal energy storage (STES) systems are key components for district heating as they offer the dispatchability and flexibility for integrating renewables into those systems. Therefore, thermal behaviour of such systems is of interest. It 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 are numerically modelled. The model considers the storage system and the surroundings around the storage. Then, the temperature distribution in the storage and the ground is investigated. In particular, thermal stratification in the storage is examined and, finally, heat storage's interaction with the surrounding ground is illustrated.
Keywords: TTES, PTES, Groundwater, Numerical modelling, Stratification.

INTRODUCTION

Nowadays, the energy demand in the buildings sector (i.e. space heating and domestic hot water) accounts for more than one-third of the total energy demand in the European countries. Thus, the European Union has supported several research projects to improve the buildings' energy efficiency. As a principal part, district heating (DH) approach has been often used to meet the buildings' heating demand as it enhances the transition to sustainable energy utilization, thus, developments of these systems have grown rapidly in the last decade (Sartor, 2017). Additionally, EU has sponsored a series of policies, plans and actions to promote the European energy scheme. One of the crucial objectives is to enhance the exploitation of renewables in DH systems to substitute the fossil fuels and, thereby, many goals can be realized (e.g. efficient utilization of renewables, less CO_2 production) (Tulus et al., 2016). Out of all renewables, the solar energy appears to be the most promising alternative energy source compared to the fossils and, therefore, central solar heating plants have received a great attention in literature (Guadalfajara et al., 2015).

Yet, it is widely evident that the heat availability from renewables and buildings' heating demand vary mostly with asynchronous pattern, which is often observed as a result to the large variation in the outdoor temperatures between summer and winter (Xu et al., 2018). Take the solar energy as an example, the mismatch is observed between the solar heat availability in summer and the high space heating demand in buildings during winter season. Thus, the major drawback of renewables is the non-dispatchability as they fluctuate daily, weekly and seasonally. As a result, a significant amount of heat might be lost during the summer season, when the buildings' heating demand is commonly minimal. Accordingly, large-scale thermal energy storage (TES) represents a good opportunity for compensating the seasonal mismatch observed between energy supply and demand (Stutz et al., 2017).

SEASONAL THERMAL ENERGY STORAGE IN DH SYSTEMS

In order to bridge the gap between solar heat abundance in summer and the space heating demand in winter, a seasonal thermal energy storage (STES) is required (Sarbu, I. and Sebarchievici, C., 2017). Nevertheless, STES systems are frequently seen challenging, and this is due the large volume and space availability required for the storage (Xu et al., 2014). For instance, if a seasonal tank TES has a size more than 100,000 m^3, then more efforts are needed to build a free-standing tank (Ochs, F., 16 - 19 September 2014) and, accordingly, those systems are mostly buried either fully or partially under the ground forming the so-called underground TES (UTES) systems (Ochs, F., 2009).

The most common types of UTES following construction criterion are: 1) Aquifer thermal energy storage (ATES) system, 2) Borehole thermal energy storage (BTES) system, 3) Tank thermal energy storage (TTES) system, 4) Pit thermal energy storage (PTES), and 5) Cavern thermal energy storage (CTES) system (Novo et al., 2010).

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In DH applications, water is commonly used as heat carrier and, subsequently, it is the storage medium for UTES systems integrated in DH systems. Its availability, low cost, chemical stability, high heat capacity and the operative temperature range make all together water as a suitable storage medium in UTES (Heier et al., 2015). Some kinds of UTES systems rarely employ the ground (e.g. rock, soil/sand) as storage media but they are not considered further in this study. Therefore, TTES and PTES systems are the focus of this study as they employ hot water as storage medium.

LITERATURE REVIEW

Large-scale TES systems are often seen as viable means for energy conservation and, therefore, research has been ongoing to address their modelling. This is also because construction of large-scale TES tends to be costly and, accordingly, the importance of modelling is strongly highlighted as an effective approach to achieve the economic and technical feasibilities.

Thermo-hydraulic modelling of large-scale TES systems is an extensive work that requires high computation efforts. However, it is important to understand how these systems firstly work. TTES and PTES systems usually operate utilizing stratification that is mostly driven by thermal buoyancy. In stratification, the hot water, which flows into the tank, eventually gathers at the top of the tank due to thermal buoyancy, whereas the cold water gathers at the bottom of the tank because of its higher density. This natural physical process generates a thermocline region that is situated between the hot and cold regions (Li, 2016). The importance of the thermocline region is that it works as a dynamic natural barrier preventing the hot water from mixing with the cold one. Therefore, the smaller the thermocline region, the less the mixing effect is and, accordingly, better stratification.

Therefore, thermo-hydraulic modelling of tanks has been widely investigated in literature reporting stratification and its influence on system performance, tank design, thermal losses etc. Yet, there have been poor efforts to investigate such a phenomenon in large-scale TTES and PTES systems and its relation directly and/or indirectly with geometry of large-scale storage considering the surroundings (soil, groundwater).

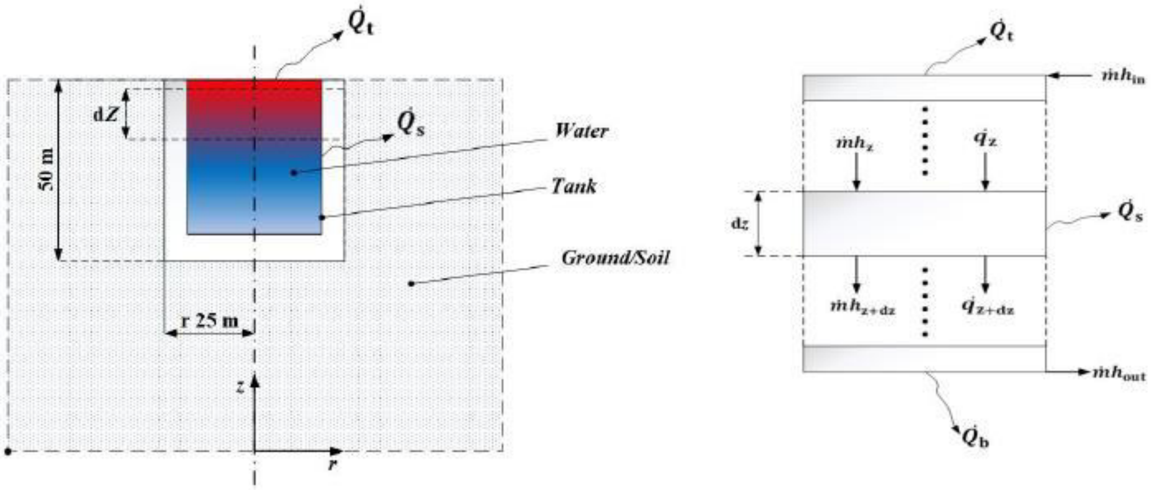
For instance, Panthalookaran et al. (Panthalookaran et al., 2008) presents numerical CFD models that are experimentally validated for charging/discharging against monitored data from two buried storage tanks in Germany. One is located in Hannover–Kronsberg with a total volume of 2,750 m^3, whereas the other is the existing underground storage 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 storage mode large-scale stratified hot water tanks was developed by utilizing these two models (Panthalookaran et al., 2011).

The simulation of CFD models requires large computation efforts in order to solve the partial differential equations for large-scale tanks and, currently, this is often seen not feasible and also in the near future (Ochs et al., June 14-17, 2009). Therefore, assumptions are frequently made in geometry, material properties and boundary conditions for the simulation, which produces a notable reduction of the computation efforts forming the so-called “coarse models” (Ochs, F., 2009). 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. Yet, research has been ongoing reporting coarse models for large-scale TES. For example, Ochs (Ochs, F., 16 - 19 September 2014) presented a dynamic numerical model based on finite element discretization. The model is able to represent various construction shapes (cylinder, cone, or pyramid stump) 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 TTES and PTES 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 increasing above 20°C to 25°C. This increase in temperature is usually seen due to the long storage 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 presents a detailed axial symmetrical model for a circular cross-sectional systems (i.e. conical pits and 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 storage and the ground.

NUMERICAL MODELLING

Modelling of thermal hydraulic behavior hot water tanks is a challenge. The few available models are appropriate for the rough sizing of the tank system, whereas the aforementioned models require large computation efforts beside some additional works to include the surroundings in the modelling. Therefore, a new numerical axial symmetric model is developed using COMSOL Multiphysics in which the model is discretized in a finite element fashion as shown in Figure 1. It is worthy to mention that the overall model consists of compiling two component-level models. One component-level model is the storage 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.



(a): Underground tank with surroundings (b): Finite differential element of the tank

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

The model is suitable only for axial symmetric geometries (e.g. truncated cones or cylinders) for the time being. However, there are ongoing efforts to develop the model into a parameterized model that simulates different geometries (e.g. pyramid stump). The impact of the soil and the groundwater on the thermal losses from the tank and the stratification can be investigated and, accordingly, the thermal behavior and the water temperatures can be depicted. Therefore, the model can perform simulation-based optimizations to determine the optimum distribution of insulation around the storage to minimize the thermal losses. Moreover, the model depicts the temperature of the ground, which helps in return in determining whether regulations with respect to the ground (temperature below 20°C to 25°C) are violated. Accordingly, many configurations can be proposed to insulate the tank and its impact on the groundwater resulting in keeping the temperature below 20°C to 25°C.

In the 1-D tank model, it is imposed that the mass of the water flowing into/from the tank is conserved and, thus, the steady-state continuity equation for the water is given as follows:

$$\dot{m}in=\dot{m}out=\dot{m} \qquad \text{(Eq.1)}$$

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

$$\frac{\partial E(t)}{\partial t} = \dot{m} \cdot (h_z - h_{z+dz}) + (\dot{q}_z - \dot{q}_{z+dz}) - U_{wall} \cdot A_{side}\big(T(t) - T_{ground}(t)\big) \quad \text{(Eq.2)}$$

$$(\rho A c_p)\frac{\partial T(t)}{\partial t} = -(\rho A c_p v)\frac{\partial T(t)}{\partial z} + A\frac{\partial}{\partial z}\left(\lambda_w \frac{\partial T(t)}{\partial z}\right) - U \cdot (\pi d) \cdot \big(T(t) - T_{ground}(t)\big) \quad \text{(Eq.3)}$$

In equation (3), v denotes the mean velocity of the fluid, while ρ and cp represent the density and specific heat capacity 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 other heat loss terms ($\dot{Q}_t$ and $\dot{Q}_b$) are accounted for. Therefore, A_{top} and A_{bot} are used to include the top and bottom surface areas of the first and last segments, respectively, in calculations. Also, it is assumed that the tank volume is divided into a finite number of segments. Moreover, the heat transfer equation in the 2-D ground model can be described as follows:

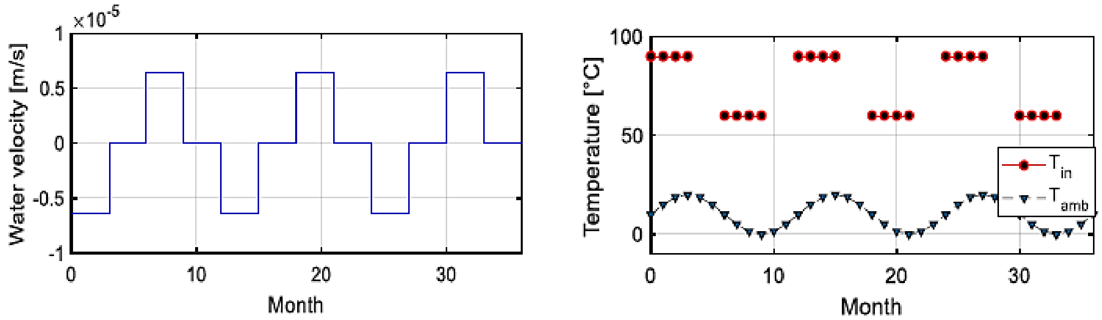
$$(\rho_g c_{pg})\frac{\partial T_{ground}(t)}{\partial t} = \frac{1}{r}\frac{\partial \dot{q}_r}{\partial r} + \frac{\partial \dot{q}_z}{\partial z} \quad \text{(Eq.4)}$$

$$(\rho_g c_{pg})\frac{\partial T_{ground}(t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \cdot \lambda_g \frac{\partial T_{ground}(t)}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_g \frac{\partial T_{ground}(t)}{\partial z}\right) \quad \text{(Eq.5)}$$

Table 1 shows a list of parameters used for the simulations and Figure 2 displays the values used for the charging and discharging variables (velocity, temperature) as well as ambient temperature.

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}	0.15 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	



(a): Water inlet velocity (b): Ambient and water inlet temperatures

Figure 2: Exemplary model input parameters over the simulation period (36 months)

RESULTS

In order to avoid complex simulations, simplified charging/discharging scenarios were chosen (see Figure 2) and this allows also to evaluate the stratification in the storage. During charging, the inlet temperature is always set to 90°C, whereas set to 60°C during discharging. Here only the results for long-term storage will be presented. Also, the investigation period is set to 36 months (3 years) in which one cycle is performed within a year.

Figure 3 reveals the amount of energy stored in the storage (tank or pit) within the investigation period (36 months). At the beginning of simulations, the storage 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 maximum energy content is reached after 3 months. Next, the energy is stored for 3 months (half a year). It is important to mention that some heat is obviously lost during the storing phase as the stored energy decreases until the point at which the discharging phase starts. This is also confirmed by temperature profiles for water in the tank and the pit (see Figure 4 (a-f)).

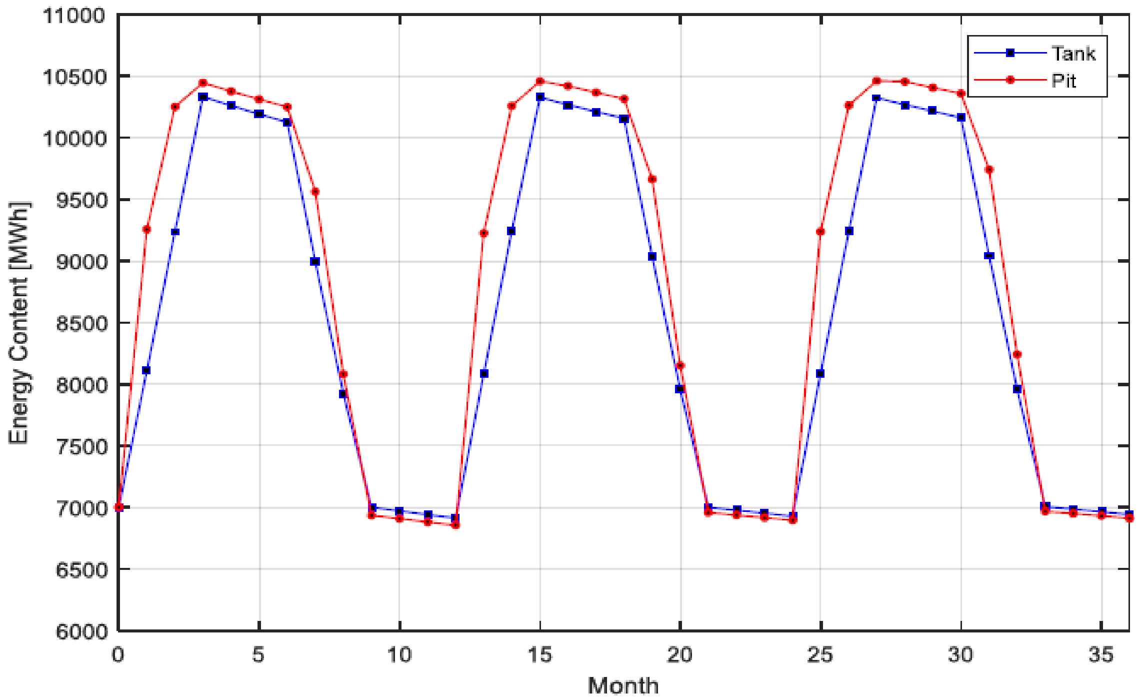
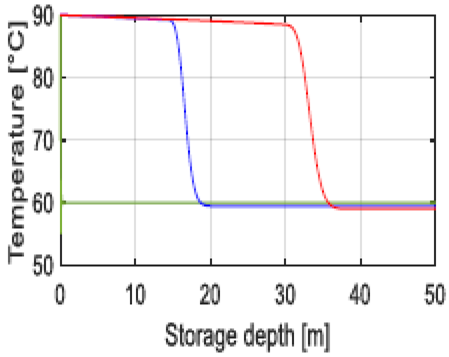
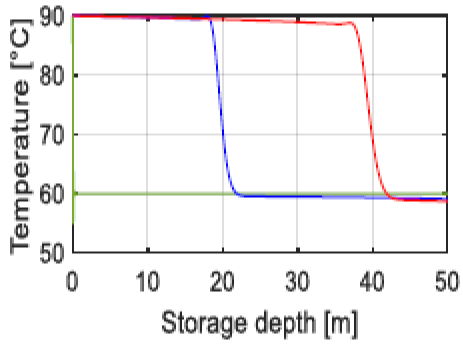


Figure 3: Energy stored in the underground storage over 36months

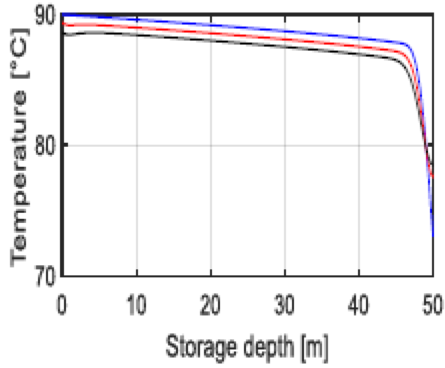
In Figure 4 (a-c), it is clearly proven that charging temperature reaches 90°C and, then, the storing phase takes place as the tank is fully charged. Whilst the discharging phase starts at a temperature below 90°C. This demonstrates that thermal losses are accounted in the model. Whereas Figure 4 (d-e) emphasizes that the temperature in the pit tends to be higher than that in the tank and, therefore, better stratification profile during storage phase can be obtained as shown in Figure 4 (b, e). Yet, the pit discharges water with a temperature during almost similar to that of the tank (see Figure 4 c, f). Under the considered conditions in simulation, Figure 4 (c, f) reveals that the pit tends to discharge faster than the tank as proven by the black line. Moreover, Figure 4 (e, f) depict an oscillation for the temperature distribution profile in depth from 0 to 5 m and the reason for this behavior is not clear at present and has to be investigated in future works.



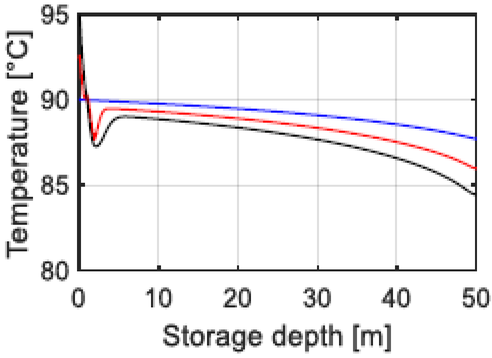
(a): Charging mode in tank



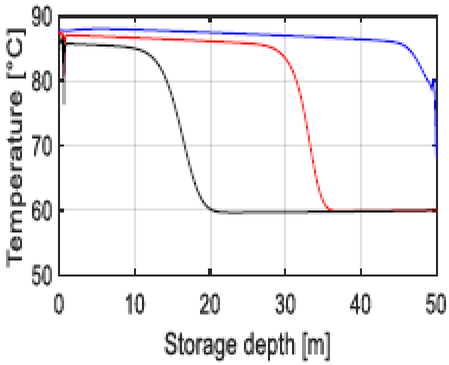
(d): Charging mode in pit



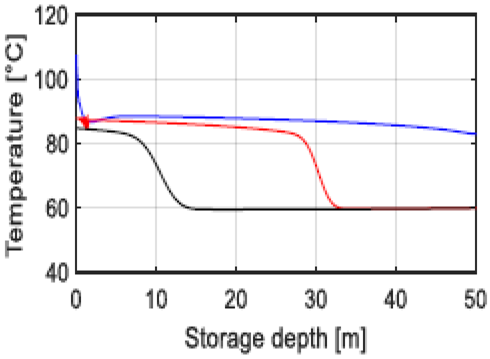
(b): Storage phase in tank



(e): Storage phase in pit

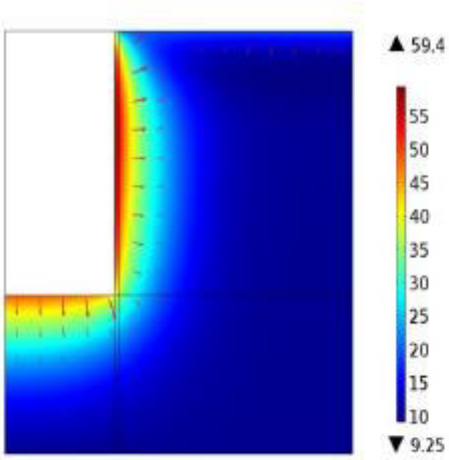


(c): Discharging phase in tank

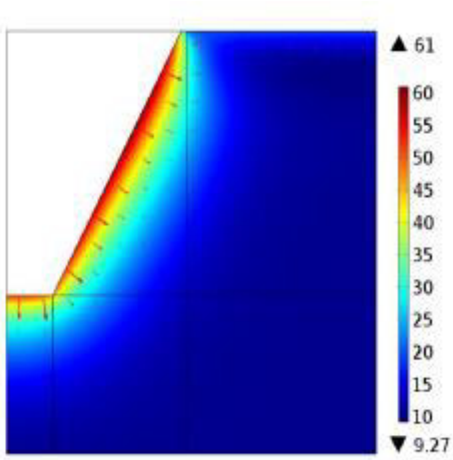


(f): Discharging phase in pit

Figure 4: Temperature profiles of water in the tank and the pit during the three operating phases of a tank storage (charging, storing and discharging)



(a): Tank



(a): Pit

Figure 5: Contour plots for the surroundings of the storage during the storage phase at the 3rd year

CONCLUSION

Large-scale TES systems are increasingly in demand for solar-assisted DH applications. Therefore, research has been ongoing to address those systems and their benefits for the overall energy scheme. Thus, an axial symmetrical 1-D tank model and an axial symmetrical 2-D ground model were developed and coupled, then, the models were tested with exemplary charging/discharging profiles (flowrates and temperatures) to examine the stratification in the tank and the pit, respectively. The models are 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 possible to perform optimization with regard to thermal losses. The results depict that stratification takes place inside the tank and the pit storage over time and this implies that the thermo-hydraulic behavior of the storage medium is correctly implemented (see Figure 4 a-f). Also, the results reveal that the ground is highly influenced during the storage phase in which the surroundings temperature exceeds 50°C (see Figure 5). Therefore, it can be said 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. Also, the model experiences low computation efforts as it simulates an underground storage system over 36 months within a duration of 22-25 minutes for the tank, whereas it costs 26-29 minutes for the pit due to more edges and complex boundaries. Yet, the results impose imposes that the models are reliable.

Future works will primarily focus on validation process to test the reliability of the model. Also, parametrizing the model through LiveLink feature that couples COMSOL Multiphysics with Matlab is one of the milestones in the near future works. This could help in realizing different geometries (e.g. truncated pyramid) not only the cylindrical ones. Moreover, future developments will examine the influence of different aspect ratios (H/d) on thermal losses from the storage and how the losses can be effectively minimized, particularly in presence of groundwater.

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