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Development of a Numerical Model for Large-Scale Seasonal Thermal Energy Storage for District Heating Systems

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Abstract

The integration of a water–based thermal energy storage system in district heating networks allows increasing the share of renewables in the energy scheme, but it requires a proper pre-design phase in which the modeling of the storage system is adequately driven.

In this context, COMSOL Multiphysics is a powerful tool that allows coupling the different domains (water, envelope and ground) through a finite element model.

A proper study of the fluid domain requires the use of momentum- and energy-conservation equations. However, the use of computational fluid dynamics in multi-annual simulations of large structures involves a significant computational effort. The development of a simpler model using only the energy-conservation equation can be particularly useful in the early design phase. A drawback of the utilisation of such a simplified model is the absence of adequate equations to describe the buoyancy, which leads to the characteristic thermal stratification. Proper adjustments (defined buoyancy sub-models) are thus applied to consider the effect of buoyancy forces on the temperature distribution and therefore on the distribution of thermal losses.

Keywords

District heating, Seasonal thermal energy storage, Buried TES, numerical modeling, TES performance

Introduction

In the last decades, global warming has become an important issue. Many countries have introduced policies to reduce greenhouse gases emissions, but the path towards a complete energy transition is still long.

Considering the heating demand in buildings in winter, the use of low efficiency domestic boilers often leads to a peak of greenhouse gases and particulate matter emissions. The adoption of a heating plant enables to improve the overall heat production process. The heat is then distributed to the customers via a network of insulated pipes using pressurized water as medium. Such systems are known as District Heating (DH) systems. Given the bigger size with respect to the domestic plants, the heat used in DH networks can be produced starting from several sources and technologies; not only fossil fuels, but also Combined Heat and Power (CHP) plants, biomass, geothermal, heat pumps, incineration, waste heat and solar energy can be used. A drawback of this technology is the fact that often users' demand and heat production or availability are mismatching with respect to each other: solar energy, for example, undergoes daily and seasonal oscillations, which make it an undispatchable source. A solution to decouple the heat demand and its availability is represented by the addition of a Thermal Energy Storage (TES) to the DH network, which can be used to store energy when available and release it when required. A simplified sketch of the working principle of a TES is provided in **Figure 1**.

TES systems are distinguished in short-term and long-term storage (also called seasonal TES). For typical DH systems the required TES volume can easily reach several hundred thousand to some millions of cubic meters if a significant portion of the winter load must be covered.

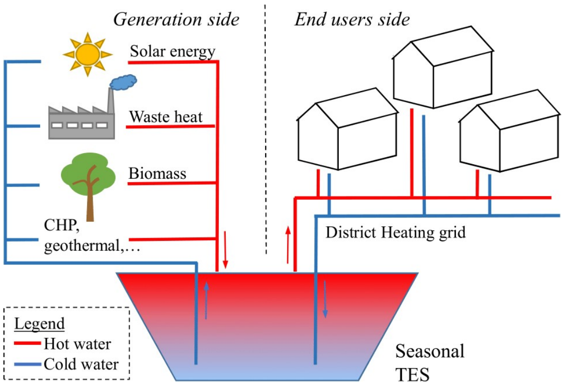

Figure 1 Basic schema of the operation principle of a seasonal TES.

In this work, the focus will be on large-scale systems, which are already employed in many countries like Denmark, Germany and Sweden [1] to store the heat available in summer and release it to the local DH grid network in winter.

Considering the scale, and thus the costs, of such a project, a preliminary feasibility study is essential to get an indication of the effective amount of energy that can be stored and of the impact of its thermal losses on the surroundings (i.e. groundwater overheating).

Several TES construction strategies can be adopted, depending on the hydro-geological conditions of the location: 1) Tank TES, 2) Pit TES, 3) Aquifer TES and 4) Borehole TES [2].

In particular, the thermal losses through the TES envelope can determine the failure or the success of such an ambitious project. Therefore, in the following pages an analysis of the thermal losses from a seasonal TES, concerning the system shape, aspect ratio and insulation characteristics is presented.

Theory

Many studies in the field of small-scale domestic TES are available [3] [4], but the shift to large-scale systems involves the addition of several parameters: ambient and ground conditions (thermophysical properties of the ground, presence of groundwater) can have a strong impact on the performance of the TES.

Water domain: thermal stratification

An accurate model of a water-based TES is possible coupling the energy and the momentum equations through a detailed 3-D Computational Fluid Dynamics (CFD) modelling. This method provides an insight into the formation and degradation of thermal stratification, a key aspect in the performance of a water-based TES.

Thermal stratification in the water domain is based on the buoyancy mechanism, driven by the difference in density between hot and cold water. The hot water gathers naturally in the upper part of the tank, while cold water remains on the bottom. The mixing layer between the hot and cold zones is commonly referred as *thermocline* [5], and acts as a dynamic barrier, which reduces the mixing in the vertical direction. A highly stratified TES (i.e. with narrow thermocline thickness) is desirable to provide the required load to the user. To exploit this natural effect the discharge devices are therefore commonly installed in the upper part of the storage system.

Thermal losses through the TES envelope enhance the mixing of the water, thus degrading the thermal stratification and reducing the performance of the TES. The geometry of the TES itself represents an important parameter in this context; the high temperature layers on the top will have a higher temperature difference with the surroundings and hence higher losses and downward flow motion.

Numerical modeling of a TES: overview

A 3-D CFD model allows taking account of the buoyancy forces, introduced by the body force term in the momentum equation. However, in the case of annual or multi-annual performance evaluations of large-scale storage systems, the computational effort (e.g. simulation time) is not anymore user convenient and simplified 1-D computer algorithms substitute 3-D CFD models.

A 1-D model, for instance a multi-node model, obeys the assumption that the temperature gradient takes place only along the vertical direction. In real TES systems vertical temperature gradients are relevant in the formation of thermal stratification. The disadvantage of such a simplified model is that the information linked to the buoyancy-driven flow due to the heat losses from the TES is lost and must be introduced by appropriate sub-models.

Finite Element (FE) method is desirable to provide higher flexibility (with respect to finite difference) in the definition of the geometry of the TES, and a more detailed analysis of the heat transferred to the surroundings (e.g. ground). An interesting example in this direction was provided by Dahash et al. [6] developing, in COMSOL Multiphysics, an axial symmetrical 1-D model of a large scale TES, including an axial symmetrical 2-D model of the surrounding ground, to investigate the performance of a cylindrical and a conical tank. This work develops this previous study with the introduction of the effect of buoyancy forces and the analysis of different TES aspect ratios, defined by the ratio between the tank height and the diameter.

Performance Indicators of a TES

Aspect Ratio (AR) is an interesting parameter that defines the geometry of the TES and its influence on its performance. Considering the same storage volume and envelope characteristics, a tank with higher AR will present an increased downward flow velocity, since the greater tank height allows an increased acceleration. On the other hand, lower ARs present a larger available horizontal area, which enhances the vertical mixing [7]. However, such parameter is not sufficient in the definition of the TES performance. When dealing for example with buried TES systems, the insulation distribution can vary for the different tank shapes, thus affecting the thermal losses.

Several other performance indicators of TES systems are available from the literature [2]. Among them, the efficiency η_{TES} compares the envelope losses to the maximum amount of energy that can be stored, as shown below:

$$\eta_{TES} = 1 - \frac{Q_{loss}}{E_{max}}$$

Computational Methods

In the presented work, a fully buried cylindrical TES (tank TES) is studied; a basic sketch is provided in **Figure 2**. The symmetry of the geometry allows the use of the 2-D axisymmetric space dimension, thus reducing the number of nodes and the computational time.

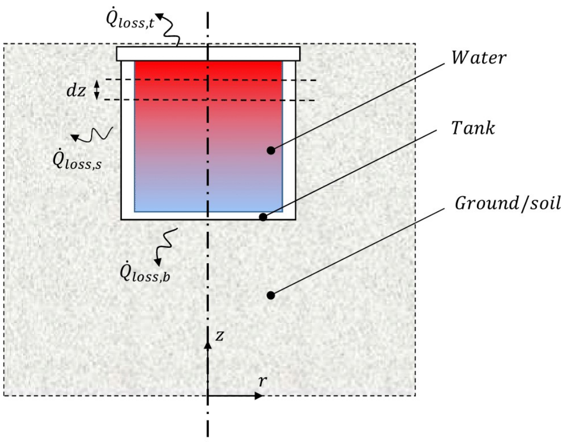

Figure 2 2-D model of the studied seasonal TES.

The water domain is defined using the PDE interface of COMSOL (*Coefficient Form Boundary PDE*) using a 1-D approach. The water domain is divided in N layers to which the energy balance equation is applied as follows:

$$\frac{dE_i}{dt} = \dot{m}(h_z - h_{z+dz}) + (\dot{q}_z - \dot{q}_{z+dz}) - \dot{Q}_{loss,\,side}$$

The terms on the right side of the equation represent, in the order, the convective heat transfer and the diffusive heat transfer within two nearby nodes and the thermal losses. Such equation is further simplified as follows:

$$(\rho A)c_p\frac{dT}{dt} = -\rho A v c_p\left(\frac{\partial T}{\partial z}\right) - A\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) - \pi D U(T - T_{ext})$$

As anticipated in the previous paragraph, the 1-D incompressible approach reduces the model complexity, but neglects the presence of three-dimensional effects, like buoyancy. This is particularly evident in the upper part of the tank, where the higher heat losses through the cover determine a formation of a low temperature layer. This does not occur in real TES systems since the warmer water, thanks to the buoyancy-driven flow, always replaces the colder water (at higher density). Therefore, a proper adjustment, here defined as *buoyancy sub-model*, is implemented. To model the additional mixing due to the buoyancy forces, an enhanced thermal conductivity ($\lambda_{w,enh}$) is introduced in the diffusive term of the PDE system, which describes the fluid domain, whenever a negative temperature gradient ($\partial T/\partial z < 0$) along the vertical direction is detected.

$$(\rho A)c_p\frac{dT}{dt} = -\rho A v c_p\left(\frac{\partial T}{\partial z}\right) - A\frac{\partial}{\partial z}\left(\left(\lambda + \lambda_{w,enh}\right)\frac{\partial T}{\partial z}\right) - \pi D U(T - T_{ext})$$

The enhanced water thermal conductivity has been defined has a function of the temperature gradient.

$$\lambda_{w,enh} = c\sqrt{\left(\frac{\partial T}{\partial z}\right)^n}$$

The surrounding ground is modelled using the *Heat Transfer in Solids* interface, which allows considering the heat transfer by conduction linked to the thermal losses from the storage, given by the following expression:

$$\rho c_p\frac{dT}{dt} = \nabla \cdot \lambda \nabla T$$

Water and envelope thermal properties are reported in **Table 1**.

The envelope of the storage is considered as a simple resistive layer, therefore only the thermal transmittance of the three elements (cover, lateral wall, bottom wall) is specified (**Table 2**).

Table 1 Thermophysical properties of the water and the soil.

	Water	Ground
λ [W/(mK)]	0.6	1.5
c_p [J/(kgK)]	4200	880
ρ [kg/(m³)]	1000	1000

Table 2 Thermal transmittance of the envelope elements.

U [W/(m²K)]	Cover	Lateral wall	Bottom wall
without insulation	0.15	90	90
with insulation	0.15	0.3	0.3

Boundary and operation conditions

Considering a seasonal TES, a complete operation cycle evolves in one year and is divided into 4 phases:

- Charging phase, when the system is charged with water at 90°C;
- Storage phase, the storage system is full, but in stand-by operation;
- Discharging phase, the stored hot water is pumped to the users and replaced by colder water at 60°C;
- Idle phase, an intermediate period between two cycles.

The ambient boundary conditions, as well as the inlet temperature values, are presented in **Figure 3**. The ambient annual temperature is modelled as a sinusoidal function, with higher values in the summer months (corresponding to the charging period) and lower values in winter (discharging period). The surrounding ground has an initial temperature of 10°C.

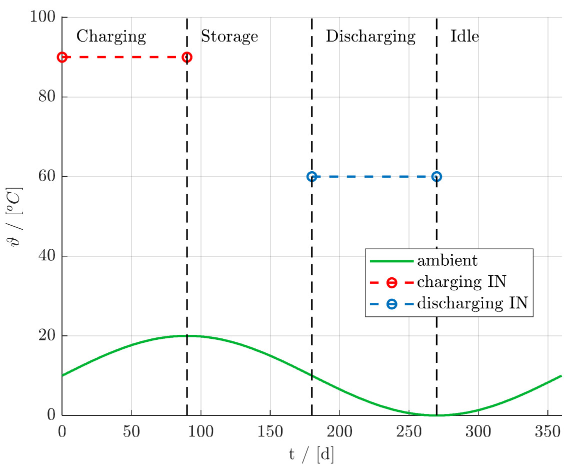

Figure 3 Boundary and operation conditions.

Simulation Results

The model described in the previous paragraph is applied to four cylindrical tanks with same volume (100 000 m^3) and different ARs (1, 0.75, 0.5, and 0.25). The same ground and envelope properties are considered in all the four simulations. A simulation period of 5 years, with a time step of 1 day, is analysed to eliminate the influence of the initial conditions and to reach a quasi-steady state behaviour.

A time-dependent simulation is used, with a maximum time step of 3 hours, a maximum number of iterations of 5 and a damping factor of (0.9). Anderson acceleration is adopted to stabilise the solution.

Tank TES with AR=1 is kept as reference case: buoyancy sub-model is applied to the water domain and the results are compared to the initial case where no corrections were applied. **Figure 4** shows the temperature profile in the water tank of AR=1 at the end of the storage phase, with and without the application of the buoyancy sub-model. As can be seen from the figure, neglecting the effect of buoyancy forces leads to a reduction in temperature in the upper water layers. The application of the buoyancy sub-model introduces a mixing term that simulates the natural convection.

The buoyancy sub-model is then applied to the list of the analysed TES systems to compare their thermal performance.

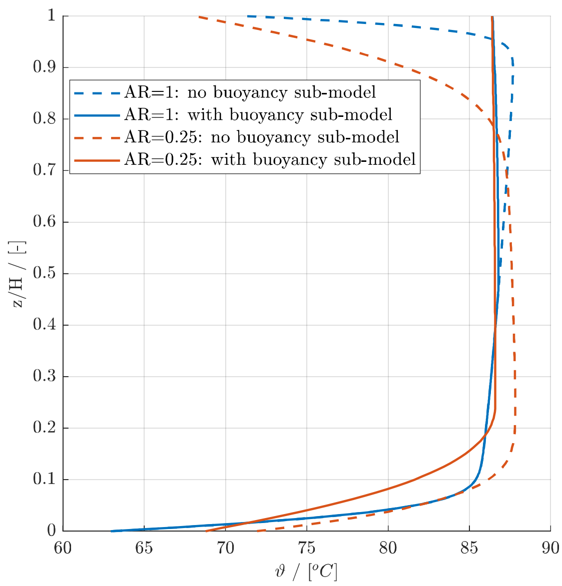

Figure 4 Water temperature profile at the end of the storage phase for the tanks with AR=1 and AR=0.25, both with insulation.

A different mesh discretisation is adopted in the solid and in the fluid domain. Details are provided in **Table 3**.

Table 3 Simulation parameters for the four TES models.

AR	Mesh elements		Simulation time [hr:mm:ss]
	Fluid domain	Solid domain	
1	50	1396	00:10:45
0.75	42	1143	00:08:34
0.5	32	859	00:08:24
0.25	20	892	00:08:30

Figure 5 shows the development of the thermal losses during the analysed period for the four studied tanks. **Figure 6** presents a bar plot with the total losses observed during the 5th year of operation, with the distinction between the three envelope elements (cover, side and bottom) for both the cases with and without insulation.

Analysing the two extreme cases (AR=0.25 and AR=1) with insulation, it is clear that the tank with AR=0.25, under the given boundary conditions, shows a total amount of losses which is 39% higher compared to the tank with AR=1. Going more into detail, the losses from the cover in the AR=0.25 case are more than doubled (+147%), while the losses from the side wall are lower (-19%) because of the smaller heat exchange surface.

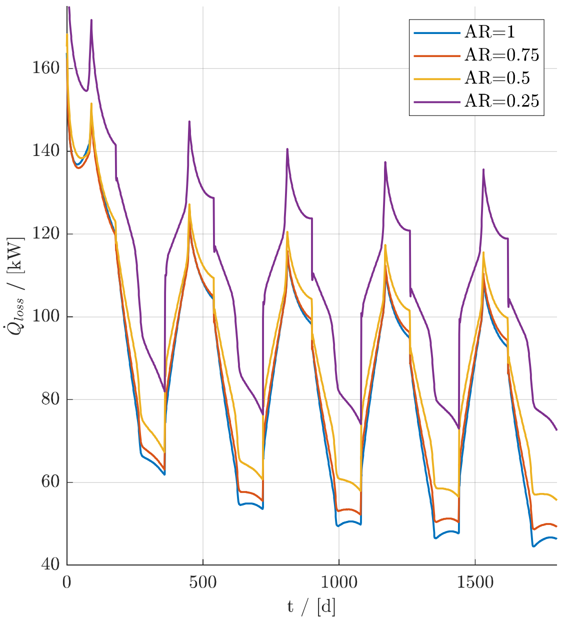

Figure 5 Profile of the thermal losses through the TES envelope during the analysed 5 years for the case with insulation.

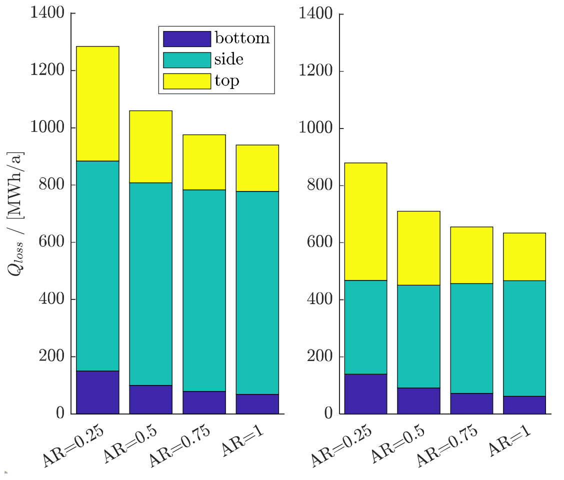

Figure 6 Total losses during the 5th year of operation: without insulation (figure **a.**) and with insulation (figure **b.**).

The AR alone is not a good measure to define the performance of a TES. In large-scale fully buried TES, the adoption of lower ARs is motivated by the generally lower costs. An insulated tank with low AR but with a good insulation shows a comparable performance with a tank with higher AR but poor insulation.

The impact of thermal losses is more clearly visible from the annual energy efficiency of the storage, as can be seen in **Table 1**.

Table 4 Energy efficiency of the 5th year of operation of the storage.

η_{TES}	without insulation	with insulation
AR=1	0.73	0.82
AR=0.75	0.72	0.81
AR=0.5	0.69	0.79
AR=0.25	0.63	0.75

Figure 7 presents the isothermal contours in the surrounding ground at the end of the 5th year charging period. The temperature distribution in the ground clearly reflects the losses distribution in TES. While the tank with AR=1 shows an higher impact on the temperature of the lateral ground, the tank with AR=0.25 presents higher losses from the bottom which affect the underneath ground.

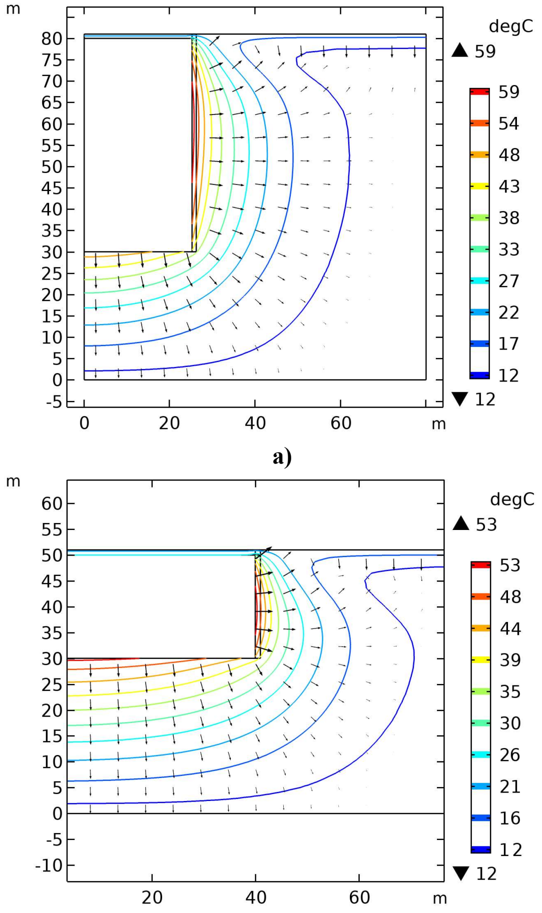

Figure 7 Isothermal contour and flux distribution for the tank TES with AR=1 (figure **a.**) and AR=0.25 (figure **b.**) with insulation.

Conclusions

The component modeling of large-scale TES yields useful indications for the performance of the system. In this level of modeling, a comprehensive analysis of the water domain, the envelope and the surroundings can be done. Such observations are particularly useful in a pre-design phase, when different TES shapes and the relative material costs are investigated. The integration of the TES in the DH network is then a further step in the overall system optimisation.

In this paper, a short and basic analysis of the envelope components was provided. Under the same boundary conditions, tank TES with lower ARs present higher losses because of the larger surface area of the cover. Being in contact with the high temperature layers of the TES on one side and with the most superficial ground on the other, this element is the biggest contributor to the total amount of losses. TES systems with higher ARs can rely on the damping effect of the ground, but present a wider lateral surface area that needs to be insulated.

The introduction of the ground water (with the interface *Heat Transfer in Porous Media*) and a more detailed modeling of the envelope (i.e. thermo-hygrometric behaviour) represent a further step in the evaluation of the mutual influence between the TES and surrounding environment.

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