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Parametric study of two-tank TES systems for CSP plants

S. Torras[a], C.D. Pérez-Segarra[a], I. Rodríguez[a], J. Rigola[a] and A. Oliva[a,]*

[a]*Heat and Mass Transfer Technological Center (CTTC) Universitat Politècnica de Catalunya – BarcelonaTech, ETSEIAT, Colom 11, Terrassa (Barcelona) 08222, Spain*

Abstract

The two-tank thermal energy storage (TES) system is the most used technology for storage in concentrating solar power (CSP) plants. This work focuses on a parametric study, which aims to identify the most important parameters on TES system, in order to improve the design and increase the performance of the plant. Three parameters have been considered: meteorological data, insulation thickness of the storage tank, and configuration of the foundation of the storage tank. The effect of each parameter is evaluated using numerical simulations based on a modular object-oriented methodology. The main issues related to the mathematical models and its numerical methodology are also presented in this paper.

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Keywords: Thermal energy storage (TES); molten salt tanks; two-tank system; numerical modelling

1. Introduction

Thermal energy storage (TES) systems can be considered a key aspect for concentrated solar power (CSP) plants, as they provide not only dispatchable electricity but also stability to the electricity network in case of high fraction of renewable production or intermittency due to weather conditions. Today, the two-tank systems using molten salt is the most used configuration within CSP plants. In this type of technology there are significant design considerations that must be taken into account, namely, avoiding the salt freezing by controlling the heat losses, storage optimization (aspect ratio, design of the inlet ports, etc.). A profound knowledge of the thermal and fluid-dynamic

* Corresponding author. Tel.: +34-937398192; fax: +34-937398920.
E-mail address: cttc@cttc.upc.edu

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phenomena present inside storage tanks is required for the design optimization. Efforts made for integrating this technology within commercial and demonstration plants can be found in Refs. [1, 2]. In addition to the accumulative experience acquired in the sector, optimization techniques based on computational fluid dynamic and heat transfer (CDF&HT) are becoming an important tool. One of the few CFD&HT simulations carried out for these tanks was conducted by Schulte-Fischedick et al. [3]. In their work, they coupled a CFD simulation using a RANS model for evaluating the molten salt behaviour with a finite element method for the tank walls. More recently, Rodríguez et al. [4] presented a methodology for studying the molten salt TES by coupling different levels of modelisation in which the molten salt was evaluated using large eddy simulation (LES). This paper follows the work carried out by Rodríguez et al. [4], but goes further in the concept presented. However, in this study a global model is used to solve the molten salt in order to take into account changes in the level of the fluid in the tank. Using the existing and new models implemented, a parametric study of the storage tank for CSP plants is carried out. The influence of several parameters (geometry, materials, operational conditions and meteorological data) is studied in detail. In the next section, the main aspects of numerical model are explained. After that, the reference case (section 3) and different results are presented (section 4).

Nomenclature

c_p	Specific heat capacity	λ	Thermal conductivity
D	Diameter	t	Tank container
e	Thickness	ρ	Density
$\vec{f}$	Normal direction vector	Δ	Coordinate increment
$\dot{g}$	Irradiation	σ	Stefan-Boltzmann constant
H	Height		
$\dot{m}$	Mass flow rate	Subscripts	
n	Normal direction	b	Bottom surface
$\dot{Q}$	Heat losses	$conv$	Convection
$\dot{q}$	Specific heat flux	ext	Ambient conditions
$\dot{q}s$	Solar radiation	fs	Free surface
r	Radial direction, radius	g	Gas ullage
S	Surface area	gr	Ground
T	Temperature	i	Insulation
t	Time	in	Inlet conditions
u	Internal energy	ms	Molten salt
V	Volume	out	Outlet conditions
$\vec{v}$	Velocity vector	rad	Radiation
		s	Solar radiation
Greek letters		sky	Relative to sky radiation
α	Superficial heat transfer coefficient	u	Ullage
ε	Emissivity in the infrared region	vw	Vertical wall

2. Mathematical model

The two-tank TES is considered to be formed by different elements, e.g molten salt fluid, tank foundation, tank walls, etc., which interact each other through their boundary conditions. The modular object-oriented methodology used in this work is the same as the one presented by Rodriguez et al. [4, 5]. This implementation has been performed within the NEST platform [6], which allows the linking between different elements of the thermal system. The mathematical model considers the transient behaviour of the molten salt fluid, the gas ullage, the tank walls and insulation, different configuration of the foundation, radiation exchange between the salt and the tank walls in the ullage. For a detailed description and derivation of the model, the interested reader is referred to a previously work [4]. A scheme of the energy balance at the different elements of the model and its boundary conditions is given in figure 1. A brief mathematical description is presented hereafter.

2.1. Molten salt global model

The molten salt fluid can be evaluated by means of global balances, together with the other elements through the boundary conditions. The mass and energy balances for the molten salt can be written as,

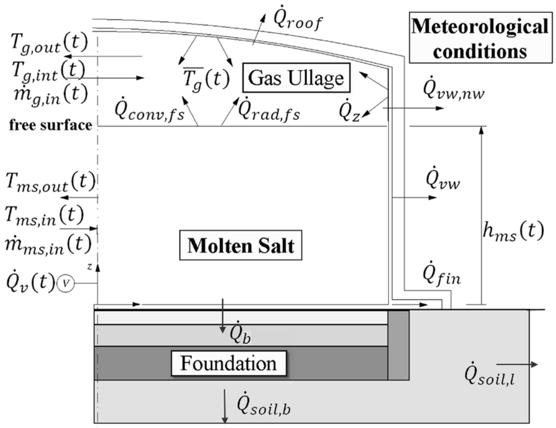


Fig. 1. Boundary conditions of the different elements of the storage tank.

$$\frac{d}{dt}\int_{Vms}\rho_{ms}dV+\dot{m}_{ms}^{out}-\dot{m}_{ms}^{in}=0 \tag{1}$$

$$\frac{d}{dt}\int_{Vms}\rho_{ms}u_{ms}dV+(\dot{m}u)_{ms}^{out}-(\dot{m}u)_{ms}^{in}=-\dot{Q}_b-\dot{Q}_{vw}-\dot{Q}_{fs}+\int_{Sms}\vec{v}_{ms}\cdot\vec{f}_{(\vec{n})}dS \tag{2}$$

In the energy equation, kinetic variation and viscous dissipation have been considered negligible. The change in internal energy and the heat flux can be interpreted as the sum of all the heat losses through the tank foundation (equation 3), the vertical walls (equation 4), and through the molten salt free surface (equation 5):

$$\dot{Q}_b=\int_{Sb}\alpha_{ms}^{b}(\overline{T}_{ms}-T_t)dS \tag{3}$$

$$\dot{Q}_{vw}=\int_{Svw}\alpha_{ms}^{vw}(\overline{T}_{ms}-T_t)dS \tag{4}$$

$$\dot{Q}_{fs}=\int_{Sfs}\left[\alpha_{ms}^{fs}(\overline{T}_{fs}-\overline{T}_g)+\varepsilon_{ms}\sigma T_{fs}^4-\varepsilon_{fs}\dot{g}_{fs}\right]dS \tag{5}$$

2.2. Tank walls and insulation

Any solid wall, including the container and the insulation material, can be evaluated by means of a transient heat balance as,

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \tag{6}$$

The above equation is evaluated for each wall layer of the object, and linked with the appropriate boundary conditions. For instance:

- With the molten salt object as, $\alpha_{ms}^{vw}(T_{ms} - T_t) = -\lambda_t \frac{\partial T_t}{\partial r}$
- With internal interfaces/ walls as, $-\lambda_t \frac{\partial T_t}{\partial n} = -\lambda_i \frac{\partial T_i}{\partial n}$
- With external conditions as, $-\lambda_i \frac{\partial T_i}{\partial n} = \alpha_{ext}(T_i - T_{ext}) + \varepsilon_i \sigma (T_i^4 - T_{sky}^4) - \dot{q}_s$

2.3. Foundation (simplified zonal model)

In [4] an advance multidimensional model was used. However, a much faster (from a computational point of view) model for the foundation has been developed considering three main zones. According to figure 2, a main zone Zt just below the tank is defined with the different foundations materials. Next to this zone, a second one, called Zs, allows for radial heat transfer losses. Finally, zone Zbc corresponds to the transient evolution of the temperature at the soil, far from the tank, and considering soil characteristics and the specific meteorological conditions.

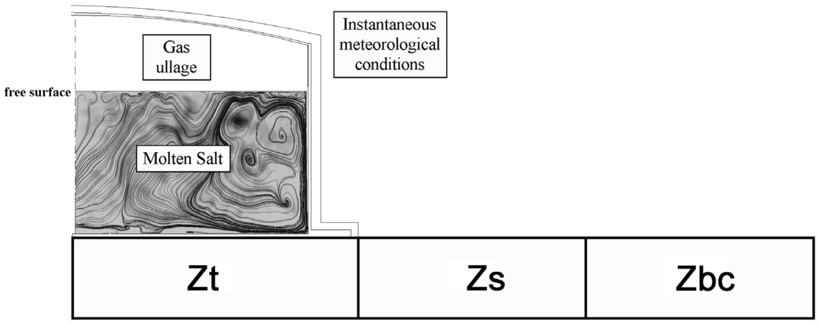


Fig. 2. Schematic representation of the foundation model.

The foundation of the storage tank (Zt) is composed of different layers; each of one is evaluated as,

$$\rho_i c_{pi} \frac{\partial T_i}{\partial t} = \nabla \cdot (\lambda_i \nabla T_i) - \dot{q}_{v,i} \qquad i = 1,2,...,N \tag{7}$$

In general $\dot{q}_{v,i} = 0$, except in the layer with passive cooling. Depending on the layer, different boundary conditions are set:

- For the surfaces at the top (first radial zone, Zt) , $-\lambda_i \frac{\partial T_i}{\partial z} = -\lambda_t \frac{\partial T_t}{\partial z}$

  (second radial zone, Zs), $-\lambda_j \frac{\partial T_j}{\partial z} = \alpha_{gr}(T_j - T_{ext}) + \dot{q}_{j,lateral} + \varepsilon_j \sigma (T_j^4 - T_{sky}^4) - \dot{q}_s$

(third radial zone, Zbc), $-\lambda_k \frac{\partial T_k}{\partial z} = \alpha_{gr}(T_k - T_{ext}) + \dot{q}_{k,lateral} + \varepsilon_k \sigma (T_k^4 - T_{sky}^4) - \dot{q}_s$

- For the internal interfaces, $-\lambda_{(i,j,k)-1} \frac{\partial T_{(i,j,k)-1}}{\partial n} = -\lambda_i \frac{\partial T_{(i,j,k)}}{\partial n}$
- For the bottom surface, $T = T_{soil}$ (soil temperature is from at some distance from the surface).

In summary, the model solves the unsteady evolution of the thermal and fluid dynamic behaviour of the tank considering in a couple manners the contribution of the different element: tank shell, salt, ullage, outdoor conditions, foundation, etc. The model considers the meteorological information with the outdoor element (unsteady weather data), the foundation can be solved using detailed multidimensional models or an unsteady zonal model, where the passive cooling can be active. The variation of the height of the molten salt is taken into account to use more realistic boundary conditions.

3. Definition of the cases and parametric studies

3.1. Definition of the reference case

The geometry and configuration for the tank modelled is a reference CSP plant defined with the data given in table 1. In these cases, cooling-down processes of the hot (T_{ms} = 565 ºC) and cold (T_{ms} = 290 ºC) storage tanks are considered. The molten salt is a mixture of 60% $NaNO_3$ and 40% KNO_3. The tank container is of steel A516gr70, and as insulation material for the lateral and roof walls Spintex342G-100 is used. Also the insulation material is covered with a thin layer of aluminium 2024 T6.

Table 1. CSP plant data.

Characteristics	Reference CSP plant
Turbine net capacity (MW_{el})	50
Technology	Central solar receiver
Operating scenario	Solar only
Solar field area (m^2)	630,000
Heat transfer fluid	Molten salt
Receiver outlet temperature (ºC)	565
Power block efficiency	0.42
Storage capacity (h)	8

Details about geometry used in the reference case are given hereafter (Fig. 3 left):

- Storage tanks internal height and radii H_{tank} = 12 m; r_1 = 11.80 m; r_2 = 12.205 m and r_3 = 12.45 m.
- The vertical wall has different thicknesses as a function the tank height, e_{v1} = 0.039 m ($0 \leqslant z \ll \Delta z$); e_{v2} = 0.032 m ($\Delta z \leqslant z \ll 2\Delta z$); e_{v3} = 0.0255 m ($2\Delta z \leqslant z \ll 3\Delta z$); e_{v4} = 0.0185 m ($3\Delta z \leqslant z \ll 4\Delta z$); e_{v5} = 0.0115 m ($4\Delta z \leqslant z \ll 5\Delta z$); e_{v6} = 0.010 m ($5\Delta z \leqslant z \ll 6\Delta z$), where Δz = 2.0 m.
- Similar to vertical wall, bottom wall also considers different thicknesses as a function of the distance from the tank centre, e_{b1} = 0.014 m ($0 \leqslant r \ll r_1$); e_{b2} = 0.021 m ($r_1 \leqslant r \ll r_3$).
- Insulation thickness: $e_{aisl} = e_{r2}$ = 0.4 m (hot tank).
- Foundation thicknesses (Fig.3 right) defined as foundation 1 (FDN 1) in the results: dry sand, e_1 = 0.006 m; foam-glass, e_2 = 0.420 m; heavy weight concrete, e_3 = 0.450 m; soil, e_4 = 9.140 m.

In addition, for the reference case the meteorological information from Sevilla is considered. The soil temperature is set at Tsoil = 15 ºC at 10 meters. For the parametric studies, the molten salt heaters and the passive cooling in the foundation were disabled.

With the CSP plant information, the geometric dimensions of the storage tanks and the meteorological data, the operating conditions of the storage tanks (inlet and outlet mass flow rate) are calculated.

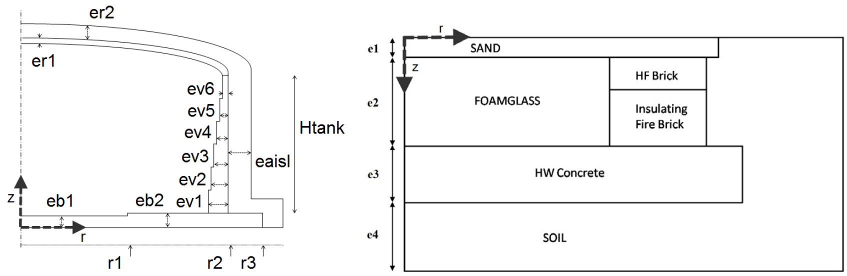


Fig. 3. Schematic representation of: (left) the storage tank; (right) the reference foundation.

3.2. Parameter candidates

Three main topics have been selected in this parametric study, meteorological data, insulation thickness of the storage tank and configuration of the foundation. To illustrate the influence of the meteorological data, four locations of interest in the CSP field were selected: Sevilla (Spain), Antofagasta (Chile), Las Vegas (United States) and Upington (South Africa), see table 2. For each one, the following meteorological information is used: variable solar radiation, wind speed and direction, relative humidity, sky and ambient temperature. Figure 4 shows the environment temperature and the direct normal irradiance.

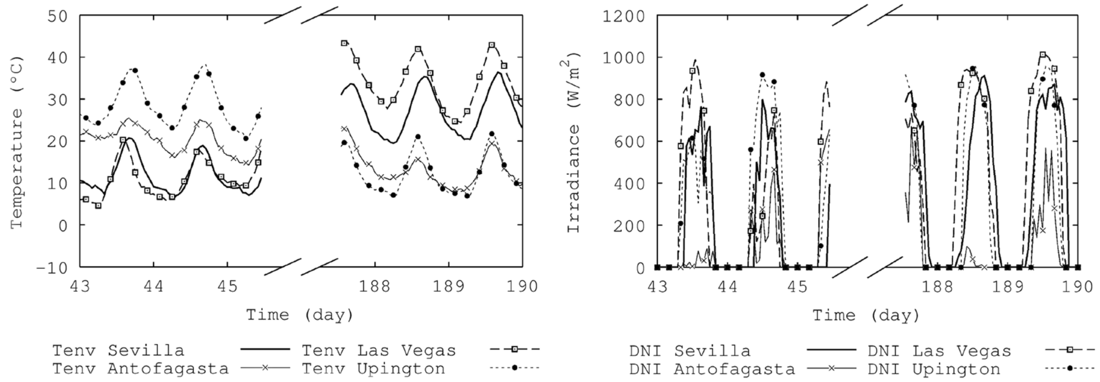


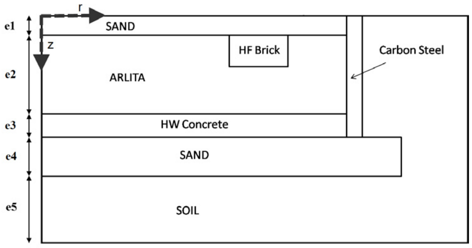
Fig. 4. Boundary conditions of the storage tank system (for different locations). Input data: (left) Ambient temperatures; (right) Direct normal irradiation.

Table 2. Selected locations with basic data.

Location	Latitude (º)	Longitude (º)	January			July		
			T_{max} (ºC)	T_{min} (ºC)	DNI (kWh/m^2 day)	T_{max} (ºC)	T_{min} (ºC)	DNI (kWh/m^{2}day)
Sevilla, Spain	37.37	5.97	21.1	3.2	3.44	39.6	16.2	7.58
Antofagasta, Chile	-23.42	70.43	30.9	9.0	4.88	31.2	3.3	3.13
Las Vegas, USA	36.08	115.01	20.7	-9.4	4.71	43.9	16.2	8.29
Upington, RSA	-28.47	-21.27	40.7	14.9	8.32	26.1	0.4	6.62

For each location, and taking into account their meteorological data, the inlet and outlet mass flow of the molten salt in the hot and cold tanks were calculated considering base load conditions. The meteorological data for each site for the 8,760 hours in a reference year was generated from the software METEONORM [7]. The essential data of the locations are given in Table 2. As mentioned above, the location for the reference case is Sevilla.

The second parameter considered in this study is the insulation thickness of the hot storage tank. Four thicknesses have been considered: 0.2 m, 0.3 m, 0.4 m (reference case) and 0.5 m. The last parameter considered is to change the configuration of the foundation of the reference case with a new one. Figure 5 shows the configuration and dimensions of the foundation of the new case foundation 2(FDN 2).



dry sand, e1 = 0.04 m;
arlita, e2 = 1.86 m;
blinding concrete, e3 = 0.450 m;
dry sand, e4 =0.30 m;
soil, e5 = 7.7 m.

Fig. 5. Schematic representation of the configuration and dimensions of the foundation is used for the parametric study.

For the parametric study of insulation thickness and configuration of the foundations the same meteorological information and the same operating conditions are used in the storage tank, as is shown in figure 6.

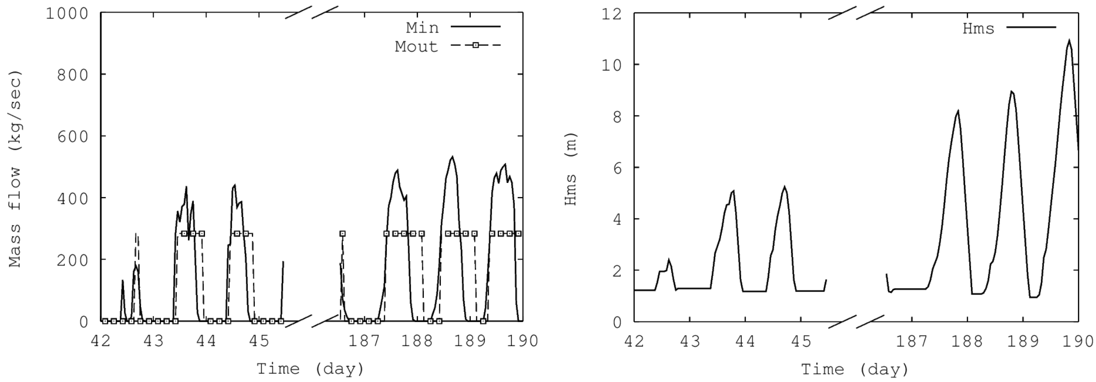


Fig. 6. Boundary conditions of the hot storage tank (for the reference case). Input data: (left) Mass flow of molten salt in operating mode; (right) Height of the molten salt.

A parametric study is then conducted using the numerical model by varying one parameter at a time. The objective is to investigate the effect of each parameter on the storage tank performance.

4. Numerical results

In order to obtain the influence of the selected parameters, different simulations have been carried out taking into account the transient behavior of the thermal energy storage system. The resulting simulation provides a year of performance data for the storage system. In order to get rid of the initial transient, a year is previously simulated before the system performance is evaluated. In the case of the foundation, due to the large thermal inertia of the materials, the performance is analysed after an initial transient of four years. Moreover, selected results are presented considering 3 consecutive days in winter and 3 consecutive days in summer.

4.1. Effect of meteorological data

The most important parameter in the meteorological data is the direct normal irradiance (DNI), which is reflected onto the receiver. The heat collected by the solar receiver from the heliostat field strongly affects the mass flow rate of molten salt that goes to the receiver from the hot tank. Four locations with different meteorological data were selected for the study. Global results of the performance of the plant are given in table 3.

Table 3. Result of the performance of the two-tanks molten salt storage for different locations.

Location	Capacity factor (%)	Full load hours (h/a)	Net electric (GWh/a)
Sevilla, Spain	0.43	3729	186.4
Antofagasta, Chile	0.36	3114	155.7
Las Vegas, United States	0.59	5203	260.1
Upington, South Africa	0.64	5590	279.5

The results in the table above correspond with the information already shown in Table 2, where the DNI for the months of January and July for each location were shown. As expected the highest the DNI the highest the plant capacity factor. Figure 7 (left) shows the comparison between the molten salt temperatures in the hot tank for the different locations. In figure 7 (right) the simulated transient evolution of the total heat loss of the molten salt in the hot tank is shown. As can be seen, heat losses vary along the day depending on the level of salt in the tank.

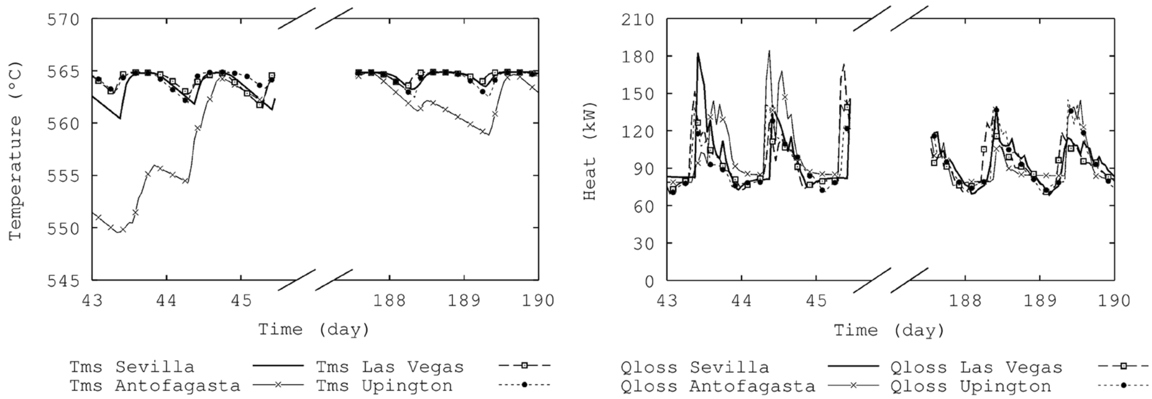


Fig. 7. Transient evolution of the molten salt in the hot tank for different location: (left) Molten salt temperature; (right) Total heat losses by the molten salt.

4.2. *Effect of the insulation thickness*

The insulation thickness affects the heat losses between the molten salt and the environment. Figure 8 (left) shows the transient evolution of temperature in the molten salt and gas ullage for the different insulation thickness. The total heat losses by the molten salt are shown in figure 8 (right). As expected, when insulation thickness decreases, the heat losses of the storage tank increases and the molten salt temperature decreases.

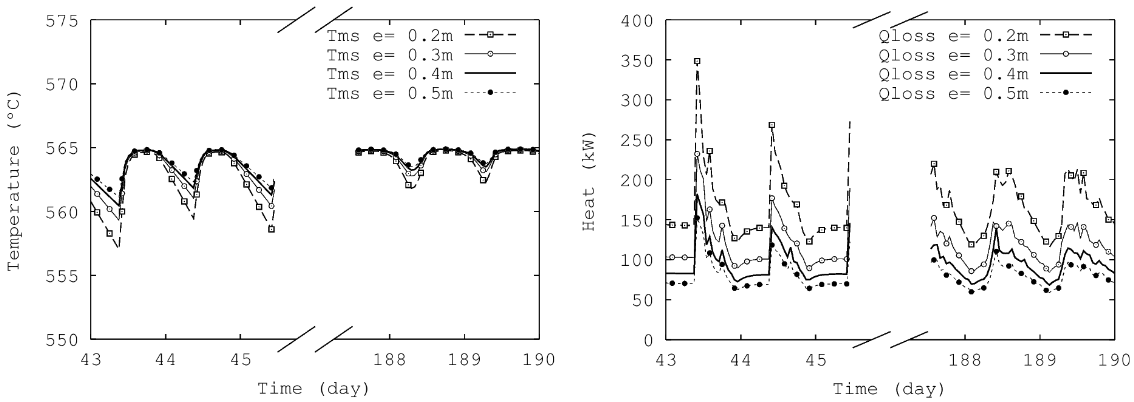


Fig. 8. Transient evolution of the molten salt in the hot tank for different insulation thickness: (left) Molten salt and gas ullage temperatures; (right) Total heat losses in the molten salt.

Figure 9 depicts the influence of the insulation thickness on the heat losses through the vertical wall (left) and the gas ullage (right).

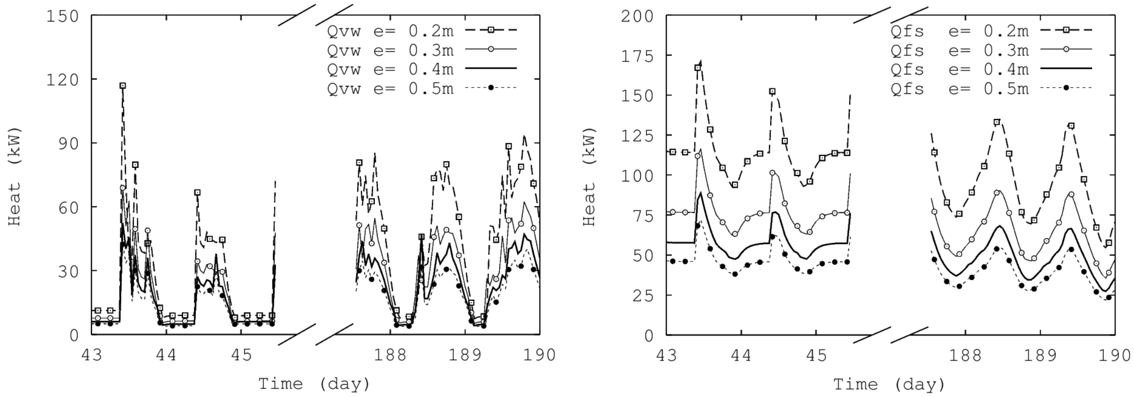


Fig. 9. Heat losses in the molten salt for different insulation thickness: (left) through the tank lateral wall; and (right) with the gas ullage.

4.3. Effect of the configuration of the foundation

Regarding the configurations and dimensions of the foundation, as aforementioned, two different configurations are considered. Results obtained for the reference case are plotted in figure 10. As can be seen, the impact of the change in configuration is of minor relevance when heat losses in the molten salt are analysed as a whole (figure 10(left)). However, a closer inspection to the heat losses through the bottom wall (figure 10(right)) reveals that there exist differences when using the second type of foundation. These differences, although small, should be considered when designing the storage as they can lead to a reduction of the operation cost of the whole system. Another advantage of the configuration FDN2 is that the cost of the foundation is reduced by 35%.

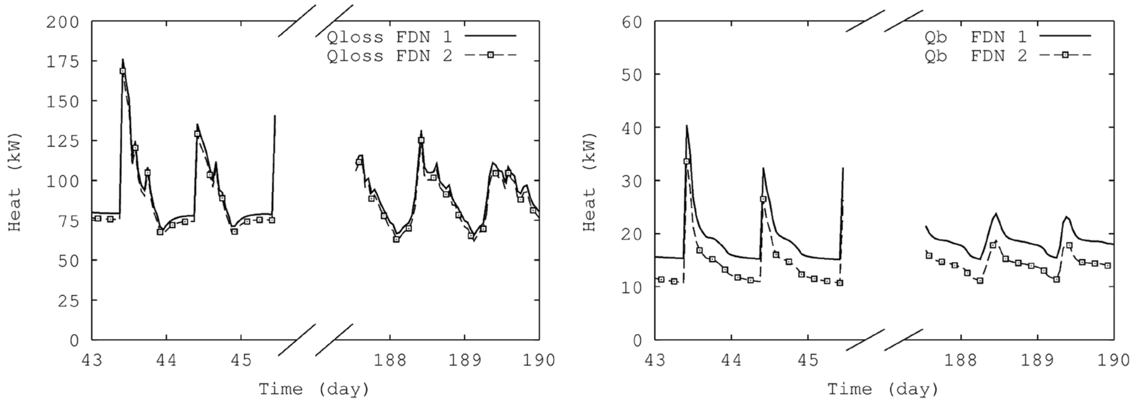


Fig. 10. (left) Total heat losses in the molten salt; (right) Heat losses in the molten salt with the tank bottom wall.

Figures 11 (left) and (right) show the temperature in the ground of the two configurations FDN 1 and FDN2, from day 29 of June of the fifth year of operation of the plant. The hot top surface can be easily seen in the close-up of the top part of the domain, which shows how the temperature changes along the depth of the ground.

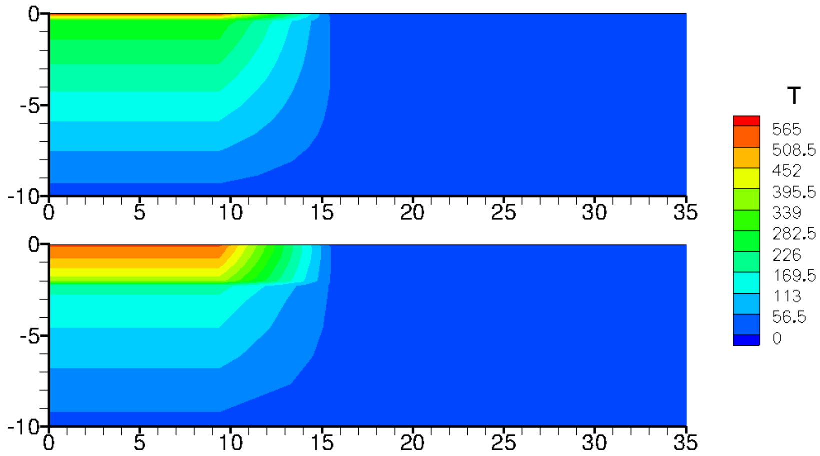


Fig. 11. Temperature in the ground for different configuration of foundation on June 29 of the fifth year of operation of the plant: (up) Foundation 1 (foam glass; reference case); (down) Foundation 2 (arlita).

5. Conclusions

This paper presents a parametric study of the hot storage tank for CSP plants. Different parameters have been considered for studying their effects on the performance of the storage system. In this work, a modular object-oriented methodology has been used. Three parameters have been considered: meteorological data, insulation thickness of the storage tank and configuration of the foundation of the storage tank. The influence of the normal direct radiation (DNI) on the operating conditions of the tank, and consequently on the plant performance has been evaluated. The thickness of the insulation of the tank is an important parameter in the design of the tank in order to reduce the heat losses of the molten salt with the external environment. Finally, it can be said that even though the configuration of the foundation has not a great influence on the heat losses, it is important to take it into account for the design of the storage tank, as its configuration and dimensions would affect the ground temperature around the tank.

Acknowledgements

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References

[1] Ortega J, Burgaleta J, Tellez F. Central receiver system solar power plant using molten salt as heat transfer fluid. Journal of Solar Energy Engineering 2008; 130:1-6.
[2] Relloso S, Lata J. Molten salt thermal storage: a proven solution to increase plant dispatchability. Experience in Gemasolar Tower plant. Proceedings of SolarPaces Congress 2011.
[3] Schulte-Fischedick J, Tamme R, Herrmann U. CFD analysis of the cool down behaviour of molten salt thermal storage systems. Proceedings of Energy Sustainability 2008.
[4] Rodríguez I, Pérez-Segarra C D, Lehmkuhl O, Oliva A. Modular object-oriented methodology for the resolution of molten salt storage tanks for CSP plants. Applied Energy 2013; 109:402-414.
[5] Rodríguez I, Pérez-Segarra C D, Estruch O, Oliva A, Lehmkuhl O. Towards the high performance computing of molten salt tanks for CSP plants. Proceedings of the SolarPACES Congress 2012.
[6] Damle R, Lehmkuhl O, Colomer G, Rodríguez I. Energy simulation of buildings with a modular object-oriented tool. Proceedings of the ISES World Conference 2011.
[7] METEONORM 4.0, 1999, Meteotest Fabrikstrasse 14, CH-3012 Bern, Switzerland.