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# Temperature distribution and heat losses in molten salts tanks for CSP plants

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ABSTRACT

Solar power plants have been deployed in the last 20 years, so the interest in evaluating their performance is growing more and more. In these facilities, thermal energy storage is used to increase dispatchability of power. The two-tank molten salts storage system with "solar salt" (60 wt.% $NaNO_3$ and 40 wt.% $KNO_3$) is the one commercially used today. To be able to achieve a deep understanding of the two-tank solar storage systems with molten salts, in 2008 a pilot plant was built at the University of Lleida (Spain) and the experimental evaluation of the temperature distribution inside the tanks and their heat losses are presented in this paper. Therefore, this pilot plant is equipped with several temperature sensors inside the tank as well as in the different layers of external insulation. As expected, temperature is lower at the external part of the tank (near the cover, at the bottom and near the walls) and no stratification is seen. It is found that the influencing parameters in the temperature distribution of the salts inside the tank are: insulation, and the existence of different electrical resistances and the orientation and surroundings of the tank. Heat losses were measured and compared both with a simulated 1-D steady state model and previous literature. Measured heat losses were from 61 $W/m^2$ through the bottom to 80 $W/m^2$ through the walls (with 73 $W/m^2$ through the cover).

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## 1. Introduction

Sustainable and low-carbon energy technologies will play a crucial role in the energy revolution to change current trends in energy supply and use. Generation of solar thermal electricity from concentrating solar power (CSP) plants has grown strongly worldwide. In fact, CSP components and systems are coming to commercial maturity, holding the promise of increased efficiency, declining costs and higher value through increased dispatchability (International Energy Agency, 2014). Four main elements are required in these plants: concentrator, receiver, transport/storage system, and power conversion block (Gil et al., 2010; Medrano et al., 2010). Among them, thermal energy storage (TES) is recognised as the technology that increases the energy system reliability, increases the generation capacity, and reduces the cost of generation. Moreover, TES has always been associated to solar installations because of the limitation in solar availability, which does not coincide with the energy demand periods.

Several commercial solar power plants exist today (Collado and Guallar, 2013; Medrano et al., 2010). Among the different TES systems, two-tanks molten salts is the most used system. A typical scheme of such a system can be seen in Fig. 1. In this configuration, HTF from the solar field is diverted through a heat exchanger that is used to charge the thermal storage system, heating salt from the cold salt tank and storing it in the hot salt tank. When the storage system is discharged, salt from the hot salt tank is sent back to the HTF-salt heat exchanger and is used to heat HTF. The heated HTF is then sent to the power block (Gabrielli and Zamparelli, 2009). The main characteristic of two-tank configurations is that the cold and hot TES media (at respectively 298 °C and 388 °C, approximately) are stored separately and the system installation and operation is currently very well known by commercial electric power companies.

Different materials have been investigated as thermal storage fluids for parabolic trough solar power plants, but due to economic and safety reasons, the so called "molten salts" or "solar salt" (60% $NaNO_3$ and 40% $KNO_3$) is the one used today (Gabrielli and Zamparelli, 2009; Gil et al., 2010; Moens et al., 2003). As Gabrielli and Zamparelli (2009) stated, in a two-tank configuration

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**Nomenclature**

| | |
|---|---|
| $A_{Concrete}$ | heat transfer area of concrete [$m^2$] |
| $A_{cyl}$ | heat transfer area of tank walls [$m^2$] |
| $A_{sphere}$ | heat transfer area of top tank wall [$m^2$] |
| $Cp$ | specific heat of salts [J/kg °C] |
| $h$ | convection heat transfer coefficient between tanks and ambient [W/$m^2$ °C] |
| $k_{concrete}$ | thermal conductivity of refractory concrete [W/m °C] |
| $k_{Rock.wool}$ | thermal conductivity of Rockwool [W/m °C] |
| $L$ | height of the tank wall [m] |
| $Q_{Concrete}$ | heat losses through concrete base [W] |
| $Q_{FG}$ | heat losses through Foamglass base [W] |
| $Q_{Top}$ | heat losses through the top of the tank [W] |
| $Q_{Wall}$ | heat losses through the wall of the tank [W] |
| $r_1$ | outer radius of the tank [m] |
| $r_2$ | radius of the tank with Rockwool [m] |
| $T$ | temperature [°C] |
| $T_{Bottom}$ | temperature of the bottom of the tank [°C] |
| $T_{Ground}$ | temperature of the ground [°C] |
| $T_{salt}$ | temperature of the salt in the hot and in the cold tank [°C] |
| $T_{Wall.ext}$ | temperature of the Rockwool surface wall of the tank [°C] |
| $T_{Wall.in}$ | temperature of the external wall surface of the tank [°C] |
| $V$ | volume of storage tanks [$m^3$] |
| $\Delta_{X.Concrete}$ | thickness of concrete base [m] |
| $\rho$ | density of salts [kg/$m^3$] |
| $\Delta T$ | thermal gradient between wall of storage tanks and surrounding air [°C] |

of a parabolic trough solar power plant with sensible heat thermal storage, the storage tanks are amongst the most critical components. However, no deep studies of the performance of such storage tanks have been published up to now.

To be able to achieve a deep understanding of the two-tank solar storage systems with molten salts, in 2008 a pilot plant was built at the University of Lleida, Spain (Fig. 2). Such pilot plant allows the study of this molten salts storage tanks system performance while a secondary circuit incorporating thermal oil (Therminol VP1) simulates the solar energy input by the use of a 24 $kW_e$ electrical boiler.

Since the two-tanks molten salts system configuration relays on the separation of the hot and cold fluid in two different tanks, its efficiency is based on a constant outlet salt temperature when discharging, which leads to the requirement of no stratification effect in the storage tanks. Therefore, heat losses to the surroundings may represent an important factor on the TES media stratification. In this paper, to evaluate the thermal performance of this two-tanks molten salts system, both the molten salts temperature distribution and the conduction heat losses through the walls of the storage tanks are widely evaluated and discussed taking advantage of the fact that this experimental pilot plant is equipped with many temperature sensors and recording equipment which allows a detailed study that is not possible in other case studies.

There are scarce published papers on experimental heat losses in molten salts reported previously. Pacheco (2002) and Pacheco and Gilbert (1999) reported measured thermal losses in the hot and cold tank in the two-tank Solar Two facility by means of turning off heat tracing and immersion heaters over several days. They accounted for 102 kW and 44 kW in the hot and cold tank, respectively. Based on the same facility, Herrmann et al. (2004) performed a regression analysis to develop an empirical heat loss equation from the measured values. Suarez et al. (2015) calculated numerically the heat losses of the tank depending on the volume of salts inside the tank and compare it with similar numerical studies performed by Zaversky et al. (2013), Rodríguez et al. (2013) and Schulte-Fischedic et al. (2008). Those simulations reveal a very homogeneous temperature distribution in the tank where the minimum temperatures are reached near the tank surfaces, especially near the free surface and the bottom. Thus, similar results are expected in the experimental analysis presented in this study. Moreover, the heat losses are validated both with a mathematical model using EES and with a correlation published by Herrmann et al., 2004.

## 2. Materials and method

### 2.1. Materials

The storage material used in this analysis is a mixture of sodium nitrate and potassium nitrate (60 wt.% $NaNO_3$ and 40 wt.% $KNO_3$), known as 'solar salt'. Both $NaNO_3$ and $KNO_3$ are commercialized by SQM® and have a purity of 98% and 99.3%, respectively. The main properties of such materials are presented in Table 1.

### 2.2. Experimental set-up

#### 2.2.1. Pilot plant description

The experimentation was carried out at the experimental facility designed and built at the University of Lleida with the purpose of simulating the operation of the TES system of a solar power plant at a lower scale (Fig. 2). Therefore, the design is as similar as possible to real facilities regarding materials, dimensions, etc., and it is integrated by a primary and a secondary circuits. The primary circuit consists on a two-tanks storage system where the molten salt charging and discharging process take place. The secondary circuit consists on: (a) a 24 $kW_e$ electrical heater which heats up Therminol-VP1 as heat transfer fluid (HTF), simulating the solar collector field; (b) a 20 $kW_{th}$ air-HTF heat exchanger which cools the HTF down simulating the cooling technology to discharge the energy stored. The heat exchange between both molten salts and Tehrminol-VP1 fluids takes place in a plates heat exchanger (76H ALFANOVA supplied by Alfa-Laval). Measuring equipment to control, register and measure relevant variables such as flow, pressure and temperature has been integrated in the facility.

#### 2.2.2. Storage system description

The two-tanks storage system consists of two identical tanks designed and built by GREA (Universitat de Lleida, Spain). The tanks design consists on a cylinder-shaped vessel closed with a flat circular plate at the bottom and a Klöpper cover on top, where the storage material is housed. All the elements of the tanks are made of stainless steel 316 L in order to withstand the elevate temperatures, to avoid galvanic corrosion, as well as to avoid compatibility problems between the storage material and the tank itself (Goods and Bradshaw, 2004). The cover of the vessel is manufactured with some openings in order to place the measuring devices and the molten salts pump. Table 2 shows the main geometrical characteristics of the tanks as well as some of the geometric characteristics

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