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Two-tank molten salts thermal energy storage system for solar power plants at pilot plant scale: lessons learnt and recommendations for its design, start-up and operation

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Abstract

Renewable energies are main players to ensure the long-term energy supply. Solar power plants with thermal energy storage (TES) are one of the available renewable technologies which have more potential. Nowadays, there are still several aspects in the design and operation of these power plants which need to be improved, such as the correct operation of some specific instrumentation, the compatibility between TES materials and storage tanks materials, and operational process strategies. This paper presents the acquired experience during the design, start-up, and operation of a kWh scale pilot experimental facility built at the University of Lleida (Spain) together with Abengoa Research (Spain) in 2008. The versatility of this facility has allowed simulating real working conditions and therefore testing different TES systems, TES materials, solar power plant components, and operational strategies focused on TES for temperatures up to 400 ºC. In the present paper, the authors show the lessons learnt at pilot and present the main problems and limitations encountered, and give advices of this experimental set-up to extrapolate the data to real plant, to provide solutions to technical problems and reduce the cost of commercial plants.

Keywords: molten salts; two-tank; thermal energy storage (TES); concentrated solar power (CSP); lessons learnt; pilot plant

1. Introduction

The current model of economic development is based on the intensive use of fossil energy resources, which causes high environmental impacts and socio-economic imbalances. Hence, new models of sustainable development are required to accelerate the development of advanced energy technologies to address the global challenges of clean energy, climate change and sustainable development. To achieve the necessary reductions in energy-related CO_2 emissions, the International Energy Agency (IEA) has developed a series of global low-carbon energy technology roadmaps, under international guidance and in close consultation with industry [1]. Renewable energies are main players of these roadmaps. They are located close to the consumption users and they ensure a long-term energy supply. Nowadays, with the aim of reducing the dependence on foreign energy, several governments have stated different economic, social and environmental policies focused on optimizing the use of available energy resources and on increasing the environmental awareness of the society.

Among the different renewables technologies, the generation of electricity with solar energy has experienced a noticeable increase as a result of the construction of large solar farms and concentrated solar power (CSP) plants. The total photovoltaic capacity installed in the world was increased from 23 GW at 2009 to 176.2 GW at 2014. And the CSP capacity installed was increased from 600 MW to 4.9 GW [2]. Focusing on CSP plants, there are basically two commercial systems which have drawn more attention: parabolic trough and tower. A parabolic trough is a type of solar thermal collector. In a parabolic trough CSP plant, the solar field is modular and is composed of many parallel rows of solar collectors aligned on a north-south horizontal axis. Each solar collector has a linear parabolic shaped reflector that focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. The collectors track the Sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF), usually oil, is heated as it circulates through the receiver and returns to series of heat exchangers in power block where the fluid is used to generate high-pressure superheated steam. The superheated steam feeds then a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers via condensate and feed-water pumps to be transformed back into steam. After passing through the HTF side of the solar heat exchangers, the cooled HTF is recirculated through the solar field. On the other hand, solar power towers use a field of sun tracking reflectors, called heliostats, which reflect and concentrate the sunrays onto a central receiver placed in the top of a fixed tower. In the central receiver, heat is absorbed by a heat transfer fluid (HTF), which then transfers heat to heat exchangers to obtain enough superheated steam to operate in a steam Rankine power cycle [3].

However, CSP plants highly depend on the weather conditions and the discontinuities may occur when clouds block the Sun, after sundown, or in early morning when power demand steps up [4]. Hence, CSP plants need to be equipped with a back-up system if a continuous electricity generation process is required. The most common used back-up systems are the ones driven by fossil fuels, which increase the energy-related CO_2 emissions [5]. On the other hand, thermal energy storage (TES) systems have gradually been introduced in CSP plants. They are low energy-related CO_2 emissions system which allows managing the electricity generation to whenever it is most needed throughout the day, overnight, or the following day, as determined by the utility or system operator. Storage temperatures for parabolic trough plants range between 280 ºC and 400 °C, but can be above 550 ºC for tower plants. Therefore, a good integration of the TES system within a CSP plant helps buffering during transient weather conditions, adjusting the dispatchability or time-shifting, increasing the annual capacity factor, which is a performance parameter that compares the net electricity delivered by the plant to the energy that it could have produced under continuous full-power operation during a year, above 40%. TES also enables achieving full load operation of the steam cycle at high efficiencies [6-8]. However, there are some key technical requirements which need to be fulfilled for a proper integration of a TES system. These requirements are high TES material energy density, good heat transfer between heat transfer fluid (HTF) and the TES material, mechanical and chemical stability of the TES material, chemical compatibility between the TES material and the TES storage tank, complete reversibility for a large number of charging/discharging cycles, low thermal losses, and controllability of the charging/discharging processes [9-11].

As a result of the high level of competition on the world solar thermal energy market and the above-mentioned advantages of incorporating TES in CSP plants, continued research is required to reduce costs and to increase the efficiency of CSP plants. Abengoa, which is a Spanish company focused on providing solutions for sustainability in the energy and environments sectors from renewable sources, has built and manages several CSP plants located around the world (Table 1). Abengoa is at the cutting edge of developing technology for building and operating CSP plants that use TES systems. By the time of the work reported in this paper, there were still several aspects in the design and operation of CSP plants coupled with TES systems that needed to be improved, such as the operation of some instrumentation, the compatibility of materials under real operation conditions (dynamic corrosion) and test different components as electrical tracing, heaters, valves, insulation, etc.

Abengoa, prior to the installation of the first oil parabolic trough commercial plant coupled with TES, validated the TES technology through two pilot plants at different scales. The first pilot plant consisted of two-tank molten salts of 8.5 MWh_{th} located in Seville (Spain) [12],while the second one consisted of two-tank molten salts pilot plant of 0.3 MWh_{th} with same aspect ratio (ratio between height and diameter of the storage tank) than TES tanks of commercial plants, which is located at the University of Lleida (Spain). Other pilot plants for molten salts testing have been built later, such as that at Plataforma Solar de Almería (Spain) by CIEMAT, with two 39-ton salt tanks [13], at Cologne (Germany) by DLR, with one thermocline packed bed tank [14], and at Antofagasta (Chile) by University of Antofagasta, with one 1-ton salt tank [15]. They all aimed to work with the philosophy of learning in demo plants. Their configuration allows testing real CSP storage operation processes at lower scale and with the advantage of having a lot of measurement equipment to fully understand how the processes develop. The idea is to acquire knowledge in design, construction, start-up and operation with two-tank TES and provide useful information for future designs and construction of experimental and commercial plants to avoid future technical problems and to reduce the investment and operation cost of these plants.

The size of this pilot plant goes in line with the new tendency of *pretotyping* [16]. Failure is an unavoidable part of the innovation process, but some failures are much harder to take, and survive, than others. *Pretotyping* is an approach to develop and launch innovation that might help to determine if the basic design is right before investing a lot of time, resources and time to properly build it. In agreement with this concept, the pilot plant located at the University of Lleida was ideated by Abengoa and the University of Lleida as a new product or service that could fail fast, cheaply and able to test an elevate number of critical and risky operation modes, instrumentation and materials. Any change in the process, any new implementation in the optimization of it, or any preliminary study can be done with less time, resources and energy than a commercial plant. Therefore, the present paper is focused on this pilot plant facility and it is divided in three main parts: description and design of the pilot plant, operational modes of the pilot plant, and finally, the start-up and operation. In the description and design, a detailed description of the pilot plant and its components is showed, as well as the justification of the different design aspects. In the second section of this study, the operational modes that can be carried out in this pilot plant have been described. Finally, in the start-up and operation section, the different steps of the start-up process of the plant and the causes of malfunction, limitations and possible recommendations for future designs plant are showed.

Table 1. CSP Plant built or managed by Abengoa [17,18]

Name CSP plant	**Location**	**Start year**	**CSP system**	**Plant capacity**	**Operation temperatures**	**TES system**	**TES system type**	**TES material**	**Storage capacity**
Atacama-1	Atacama Desert, Chile	Under constructi on	Tower	110 MW	300-550 ºC	Yes	Direct two-tank	Molten salts	17.5 h
Solana	Arizona, USA	2013	Parabolic trough	280 MW	293-393 ºC	Yes	Indirect two-tank	Molten salts	6 h
Kaxu Solar one	Poffader, South Africa	2015	Parabolic trough	100 MW	293-393 ºC	Yes	Indirect two-tank	Molten salts	2.5 h
Khi Solar one	Upington South Africa	2017	Tower	50 MW	530 ºC	Yes	Steam storage	Steam	2 h
Xina Solar one	Poffader, South Africa	2017	Parabolic trough	100 MW	293-393 ºC	Yes	Indirect two-tank	Molten salts	5 h
Solnova 1, 3, 4	Sanlúcar la Mayor, Spain	2009	Parabolic trough	50 MW	293-393 ºC	No	---	---	---
PS10	Sanlúcar la Mayor, Spain	2007	Tower	11.02 MW	250-300 ºC	Yes	Steam storage	Steam	1 h
PS20	Sanlúcar la Mayor, Spain	2009	Tower	20 MW	250-300 ºC	Yes	Steam storage	Steam	1 h
Helionergy 1, 2	Écija, Spain	2011, 2012	Parabolic trough	50 MW	293-393 ºC	No	---	---	---
Helio 1, 2	Puerto Lápice, Spain	2012	Parabolic trough	50 MW	293-393 ºC	No	---	---	---
Solabén 1,2,3,6	Logrosán, Spain	2013	Parabolic trough	50 MW	293-393 ºC	No	---	---	---
Shams 1	Abu Dhabi, United Arab Emirates	2013	Parabolic trough	100 MW	300 ºC-400 ºC	No	---	---	---

2. Description of the pilot plant facility and design features

The pilot plant facility presented in this paper was designed and built in 2008 at the University of Lleida in collaboration with Abengoa and started to be operative in 2009 (Figure 1). This facility is mainly integrated by seven systems to simulate at lower scale a CSP plant coupled with an indirect two-tank molten salts TES system (Figure 2). The seven systems which integrate the pilot plant facility are the heating system, the cooling system, the heat transfer fluid HTF-salts heat exchange system, the storage system, the molten salts electrical heating system, the piping and valves, and the control and instrumentation system. A more detailed description of each system and their components is shown in the following sections. Most of the components described below are not standard because were specifically designed for research purposes the pilot plant, and therefore were tested for the first time.

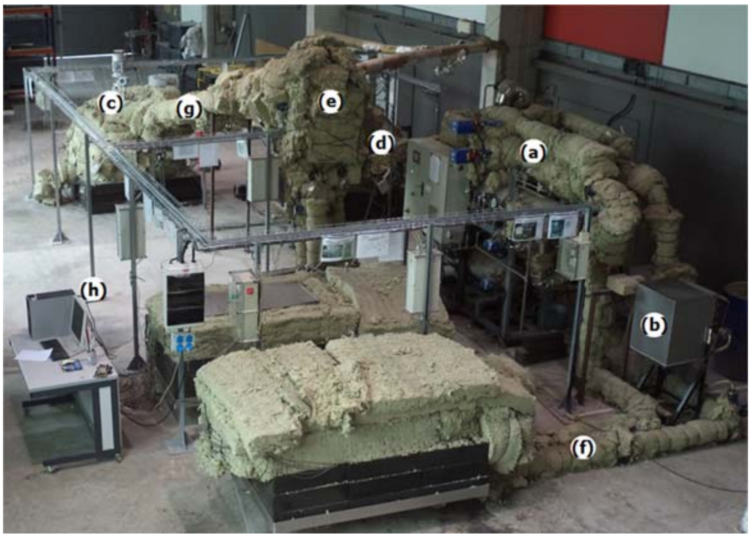
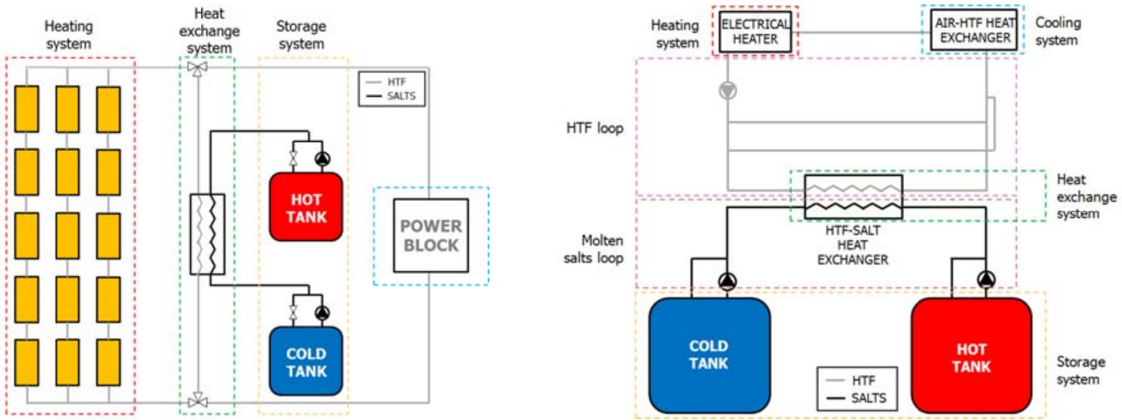


Figure 1. Overview of the high temperature pilot plant facility at the University of Lleida (Spain). (a) Electrical heater; (b) Air-HTF heat exchanger; (c) Molten salts hot tank; (d) Molten salts cold tank; (e) HTF-molten salts heat exchanger; (f) HTF loop; (g) Molten salts loop; and (h) Acquisition and recording system



(a) **(b)**

Figure 2. Comparison of the different systems existing in a (a) real solar power plant with a two-tanks molten salts TES system; and in the (b) pilot plant facility at the University of Lleida

2.1. Heating system

The heating system consists of a 24 kW_e electrical heater type CE-22 HT, supplied by Pirobloc (Spain), which heats up and controls de temperature of the HTF acting as the heating energy source during a charging process, and allowing the simulation of real operation conditions (Figure 3). In a real solar power plant this function is accomplished either at the solar field by the parabolic-trough solar collectors, or at the solar tower receiver.

The heating system is mainly composed of an HTF storage tank, where the HTF is stored and heated with an electric resistance, an expansion vessel, which withstands the HTF thermal expansion, different valves and by-passes, which control the HTF flow rate, a programmable logic controller (PLC), which electronically controls all the parameters of the HTF loop, and a pump, which pumps the HTF through the HTF loop. Moreover, a refrigeration system is needed to prevent the pump of the electrical boiler to overcome its critical working temperature (84 ºC). This refrigeration system consists of a closed circuit with a water storage tank, a circulation pump and an evaporator. Table 2 shows the main characteristics of the electrical boiler.

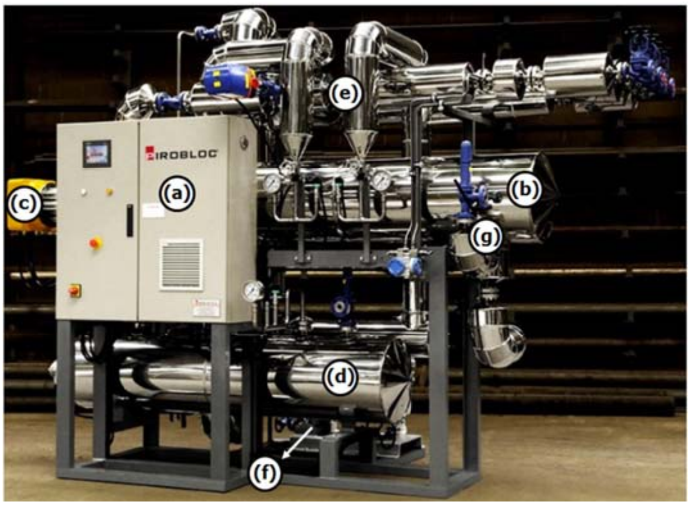


Figure 3. Overview of the electrical heater installed at the pilot plant facility. (a) PLC; (b) HTF storage tank; (c) Electrical heater; (d) Expansion vessel; (e) Valves and by-passes; and (f) Pump

Table 2. Main characteristics of the electrical heater installed at the pilot plant facility **Characteristics**	**Units**	**Value**
Electrical power	kW	24
Thermal heating power	kW	20
Flow rate range	m^3/h	0 - 3
Maximum pressure of work	bar	15
Maximum temperature of work	ºC	400
HTF pump hydraulic power	kW	3.5

Two different HTF have been tested in the pilot plant facility: the synthetic oil Therminol VP-1 [19] and the silicone fluid Syltherm 800 [20]. Peiró et al. [21] experimentally demonstrated the importance of selecting a proper HTF for improve the thermal performance of CSP plants and increase the total power that the HTF can provide and absorbed. The authors theoretically studied the properties of both HTF, based on the data given by the manufactures. Afterwards, the authors experimentally perform the comparison in a two-tank molten salts thermal energy storage pilot plant built at the University of Lleida (Spain).

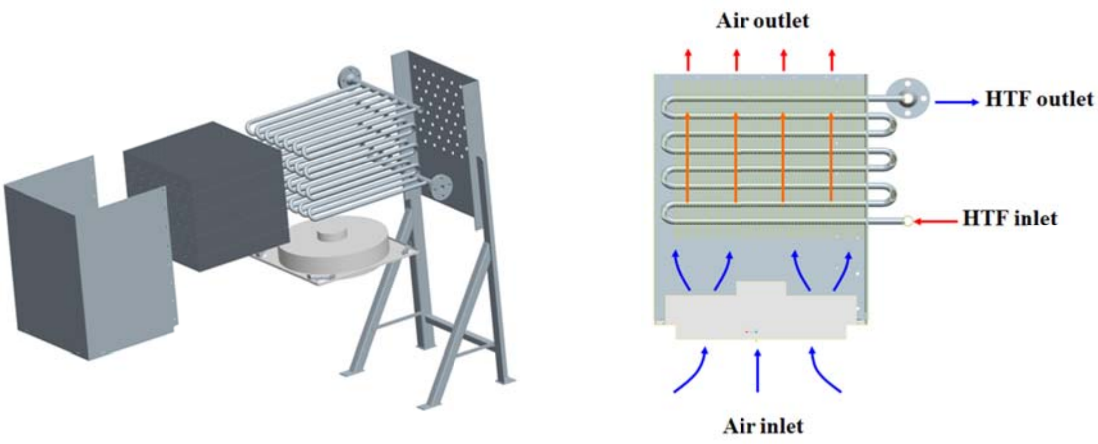
2.2. Cooling system

The cooling system is based on a 20 kW_{th} air-HTF heat exchanger, which was designed and built by the GREA research group from the University of Lleida. This system simulates the power block of CSP plants, in which the energy is transferred to the steam by means of the HTF. The characteristics of the air-HTF heat exchanger are shown in Table 3.

The design of the system is based on a cross flow heat exchanger concept. It consists of a rectangular duct with a set of fins and tubes arranged in zigzag inside, where the heat exchange is carried out by circulating air at ambient temperature with a fan through the set of fins and tubes, inside of which the HTF circulates (Figure 4).

Table 3. Main characteristics of the air-HTF heat exchanger installed at the pilot plant facility

Parameters	**Units**	**Value**
Thermal power	kW_{th}	20
HTF flow rate	m^3/h	0-3
Air flow rate	m^3/h	1800
Air inlet temperature	ºC	ambient
Pipe inlet diameter	in	3/8
Number of pipes	-	56
Number of fins	-	50
Fins heat transfer surface	m^2	15
Dimensions (Height x Width x Depth)	mm	700x540x440



(a) **(b)**

Figure 4. Air-HTF heat exchanger used as cooling system at the pilot plant facility. (a) Explode of the 3D model; and (b) scheme of the working principle

2.3. Heat exchange system

The heat exchange system consists of an ALFANOVA 76-38H plate heat exchanger from Alfa Laval, which allows the heat exchange between the molten salts and the HTF. It is the same type of heat exchanger than some commercial CSP plants and it was chosen because of its high thermal efficiency and compactness. Figure 5a shows an overview of the heat exchanger and Table 4 shows its main characteristics.

(a) **(b)**

Figure 5. Heat exchange system. (a) Overview of the plate heat exchanger; and (b) location of the heat exchanger at the pilot plant facility

The heat exchanger is installed at 2.2 m over the ground level to ensure a tilted connection (around 35 %) between the storage and the heat exchange systems (Figure 5). This slope helps the molten salts placed inside the piping to return back to the storage tanks when both the charging and discharging processes are finished, and therefore avoiding potential plugs because of the salts solidification.

In order to evaluate the heat exchange of the system, four Pt-100 1/5 DIN class B temperature sensors, with an error of ±0.3 ºC, are located at a distance of 8.5 cm from each of the four terminals of the heat exchanger (two on the HTF loop and two on the molten salts loop). The location of these sensors is mainly due to ensure a proper reading. Moreover, two surface Pt-100 1/5 DIN class B temperature sensors at the wall of the heat exchanger and at the wall of the insulation to evaluate the heat losses of the heat exchanger system to the surroundings.

Finally, 24 cm of rock wool is placed around the heat exchange system to avoid the heat losses to the surroundings.

Table 4. Thermal and geometrical characteristics of the molten salts – HTF heat exchanger installed at the pilot plant facility.

Characteristics	Units	HTF loop	Molten salts loop
Design pressure	bar	20	10
Test pressure	bar	26	13
Design temperature	ºC	400	400
Directions of the fluids	-	Both	Both
Length x Width x Height	mm	208 x 191 x 618	
Plate material	-	Stainless steel alloy 316	
Plate thickness	mm	0.40	
Number of passes	-	10 (both sides)	
Heat transfer area	m^2	3.8	
Number of plates	-	38	

2.4. Storage system

The storage system consists of two identical 0.57 m^3 TES tanks designed and built by the GREA research group from the University of Lleida. They are based on the two-tank molten salts concept of the CSP plants which is implemented by Abengoa in commercial developments. One of the TES tanks contains the molten salts at higher temperature, from now on “hot tank”, and the other one at lower temperatures, from now on “cold tank”, to create the initial conditions previous to both the charging and discharging processes

The design of the tank consists of a cylinder-shaped vessel closed with a Klöpper cover welded on the top. The material used is stainless steel 316L to withstand the elevate temperatures, to avoid galvanic corrosion, and to avoid compatibility problems between the molten salts and the tank itself. Both the tank walls and cover are manufactured with some openings with the aim of placing the electrical heaters, which are used to heat up the molten salts up to de desired temperatures, the different measuring instrumentation, and the molten salts pump. Moreover, a drainage piping is placed on the bottom of the tank to drain the molten salts from the tank.

The design of the tank was done to be as similar as possible to the ones existing in real CSP plants. It was decided to keep the same aspect ratio, which is the ratio between the diameter and the height. Regarding to the material, both the hot and the cold tanks are constructed with the same material for future research purposes, contrary to what it is done in commercial plants. Moreover, the cold tank incorporates more electrical heaters than standard commercial tanks with the aim of melting the molten salts within the tank. Table 5 shows the main geometrical characteristics of the tanks.

Table 5. Geometrical characteristics of the molten salts storage tanks installed at the pilot plant facility

Parameter	**Units**	**Value**
Material	Stainless steel 316L	
Internal Diameter	mm	1200
Cylinder height	mm	500
Klöpper cover height	mm	267
Total height	mm	767
Thickness of the walls	mm	4
Surface area-to-volume ratio	-	3.36
Aspect ratio	-	0.41

In order to move the salts from one tank to the other, a vertical centrifugal pump commercialized by Friatec-Rheinhütte was installed at the top of each tank. This pump can be also used to recirculate the salts within the same tank to homogenize the temperatures. One of the biggest problems of this type of pumps is that they are not dimensioned to work at pilot plant scale, and therefore three main adjustments were performed to adjust them to the scale of the facility. First, a reduction of the length of the shaft sleeve was done by the supplier; second, a by-pass is incorporated inside the pump, and third, variable-speed drives are connected to the pumps. These last two modifications were introduced to reduce the molten salts flow rate due to the fact that the flow rate of the experimentation carried out at the pilot plant facility is lower than the minimum flow rate that the pump provides. Table 6 shows the main characteristics of the molten salts vertical centrifugal pump installed at the pilot plant facility.

Table 6. Main characteristics of the molten salts vertical centrifugal pumps installed at the pilot plant facility.

Characteristics	**Units**	**Value**
Model	GVSO 40/160Z	
Operational flow rate	m^3/h	1.3-3
Nominal power	kW	2.5

In order to maintain the heat losses to the surroundings at values between 40 W/m^2, which are the accepted values in commercial power plants, and 80 W/m^2, which are the accepted values for experimental facilities [Dr. Cristina Prieto, Abengoa, personal communication, April 4th, 2017], rock wool is placed around the walls and cover of the tanks. Moreover, refractory concrete and Foamglass® are located under the tanks. Foamglass® was also selected because of its high compressive strength and mechanical stability at high temperatures [12]. Table 7 shows the thickness of the materials used as insulation and Figure 6 a schematic overview of the insulation.

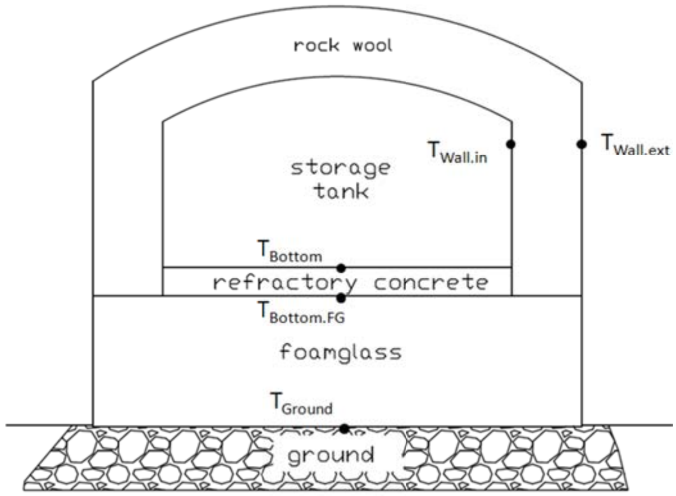


Figure 6. Schematic overview of the insulation of the storage system. Based on Prieto et al. [22]

Table 7. Characteristics of the material used as insulation for the two storage tanks at the pilot plant facility.

Insulation material (Manufacturer and model)	Units	Thickness
Rock wool (Isover SPINTEX 342G-125 and TECH WIRED MT 5.1)	mm	240
Refractory concrete (Hormirefra)	mm	100
Foamglass® (WBT4+ FOAMGLASS)	mm	450

2.5. Piping, nitrogen circuit and valves

2.5.1. Piping

The piping of the pilot plant facility is divided into two different loops: the HTF loop and the molten salts loop (Figure 2b). The HTF loop consists of a stainless steel 316 L piping of 1” of diameter. With the implementation of different by-passes, different flow arrangements (parallel and counter flow) can be achieved in the heat exchange system. The molten salts loop consists of a stainless steel 316 L of 1” of diameter which is divided in four different circuits to introduce a greater versatility to the pilot plant facility. The first circuit allows by-passing the heat exchange system. The second circuit is designed as a by-pass for the cold tank to study the reaction of different equipment such as simple valves, gaskets, etc. under the influence of the molten salts. The third circuit consists of three parallel pipes, with different diameters, which are connected to the hot tank to test the influence of the piping and the behaviour of different electrical components. Finally, the fourth circuit is another by-pass on the cold tank which goes through the heat exchanger and allows the molten salts leaving the heat exchanger to enter to the cold tank again and increase faster their temperature.

In order to minimize the heat losses to the surroundings and potential thermal bridges, rock wool is used as insulation. Two layers are placed around the piping to ensure a higher efficiency (Table 8).

Table 8. Characteristics of the insulation used on the piping of the pilot plant facility.

Insulation material	**Units**	**Thickness**
Internal layer: Rockwool shell (RWL POROX PS 964 1”)	mm	40
External layer: Rockwool (Rock wool (Isover SPINTEX 342G and TECH WIRED MT 5.1)	mm	240

2.5.2. Nitrogen circuit

Three independent nitrogen circuits are installed in the pilot plant facility to ensure proper operation conditions. The first circuit is located at the highest point of the facility and is connected to the heat exchange system. Its main objective is to drain both the heat exchanger and the molten salts loop when the processes are finished. Hence, the molten salts are forced to return to the storage tanks and solidifications can be prevented. Moreover, this circuit also helps avoiding mechanical stress of the heat exchanger plates caused by the molten salts thermal expansion. The second circuit connects the two storage tanks and the nitrogen tank. Its main objectives are to create an inert protective atmosphere inside the tank in front of a potential HTF leak, and to help draining the storage tanks when they need to be emptied. Finally, the third circuit is connected to the expansion vessel of the electrical heater HTF storage tank. Its objective is to provide an inert atmosphere in the HTF loop so to avoid fire hazards, to provide pressure to the system to absorb the oscillations in the system because of the HTF thermal expansion, and to prevent the formation of vapours.

These three circuits are connected to two electric heaters, whose power is 2 kW and 0.8 kW, to ensure a minimum inlet temperature of the nitrogen at the molten salts loop, and therefore, to prevent solidifications because of the contact between the molten salts and the nitrogen at a lower temperature.

2.5.3. Valves

Several bellow-seal valves (model ARI-FABA-Plus from A.R.I) and globe valves (model WTA 11.1-S-SE-SBV from Schubert-Salzer) are placed in both the HTF and the molten salts loops, respectively. Their hand wheels are located at 210-320 mm from the piping to improve the handling of the valve at high temperatures. The function of these valves is the modification of the flow direction of both the molten salts and HTF to adjust them to the desired operational processes and flow arrangements. The selection of this type of valves was mainly due to their resistance and operation facility at high temperatures, and the way they are connected to the piping of the different loops: while on the molten salts loop they are welded to the piping, on the HTF loop they are connected to the piping with flanges.

2.6. Molten salts electrical heating system

The molten salts electrical heating system consists of two elements: the electrical heat tracing, which is installed in the molten salts piping, and the immersed electrical resistances, which are placed inside the molten salts storage tanks.

2.6.1. Electrical heat tracing

The electrical heat tracing is an essential element for the proper operation of the high temperature pilot plant facility due to the fact that helps avoiding solidifications inside the piping, and helps maintaining a more uniform and controlled temperatures of the molten salts in the piping, especially in critical points such as curves, T's, valves, and supports, which are considered the biggest thermal bridges of the system.

The electrical heat tracing installed in the pilot plant facility is divided three different circuits. Each one has a nominal power of 2.4 kW at 230/48 Vac and consists of a series type heating cable with a mineral insulation and Inconel sheath supplied by AKO company which provides heat by the Joule effect. The division of the tracing system in different circuits was done to ensure a more accurate control of the temperatures. Therefore, it can help avoiding problems of overheating and salts solidification in the above-mentioned critical points from the molten salts loop. Each circuit is controlled by different temperature sensors, which are carefully placed to the most critical (on the surface of the pipe of each circuit and on the surface of the recirculation pipe of both tanks, cold and hot) and optimal locations along the piping to avoid the previous problems, and connected to a controller.

Figure 7 shows an overview of part of the electrical heat tracing installed on piping section which contains a valve, which is known to be a critical point. It can be seen that the heating cable is placed on the lateral sides of the piping to favour the heat transfer to the molten salts and to prevent its overheating. It is attached to the piping with metallic clamps and it is recoated with aluminium foil to avoid the direct contact between the cable and the insulation which is place above it. All the valves are recoated with a metallic mesh to increase the heat transfer surface of the electrical heat tracing and therefore avoiding salts solidification.

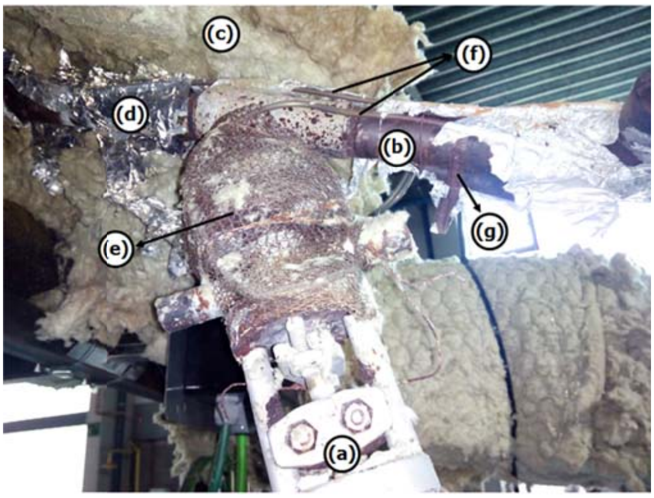


Figure 7. Overview of the electrical heat tracing of a valve and the piping after operation. (a) Valve; (b) Piping; (c) Rockwool insulation; (d) Aluminium foil; (e) Metallic mesh; (f) Electrical heat tracing; and (g) Clamp.

2.6.2. Immersed electrical resistance heaters

The immersed electrical resistance heaters placed inside the two-tank molten salts TES system provide heat to avoid the molten salts solidifications, to compensate the thermal losses to the surroundings because of the high surface-are-to-volume ratio, and to carry out the molten salts melting when they are fully solidified.

For experimental purposes, different electrical resistance configurations have been implemented in each storage tank. The cold tank contains twelve electrical resistances of 1 kW and a surface charge density of 0.8 W/cm^2, which are equally divided in two levels with a symmetric distribution of 60º (Figure 8a and Figure 8b). These resistances are protected with a metallic sheath to prevent direct contact with the molten salts. Six out of the twelve resistances incorporate four rectangular fins to increase their heat transfer surface. Some of the resistances incorporate temperature sensors between them and their sheath to monitor the temperature and to control them to reach temperatures higher than 600 ºC, which is the limit for the molten salts chemical stability. Four more temperature sensors are placed close to the outer face of some resistances contacting the molten salts to prevent the burning of salts near the resistances. The hot tank contains four resistances of 1 kW and a surface charge density of 0.8 W/cm^2, which are symmetrically distributed in 90 ºC in only one level to be as similar as in commercial tanks (Figure 8c and Figure 8d). Three of these resistances are protected with a metallic sheath and the remaining one is not protected for experimentation purposes (Figure 9). The protected resistances are controlled in the same way than ones in the cold tank, while the unprotected resistance is controlled by three different temperature sensors.

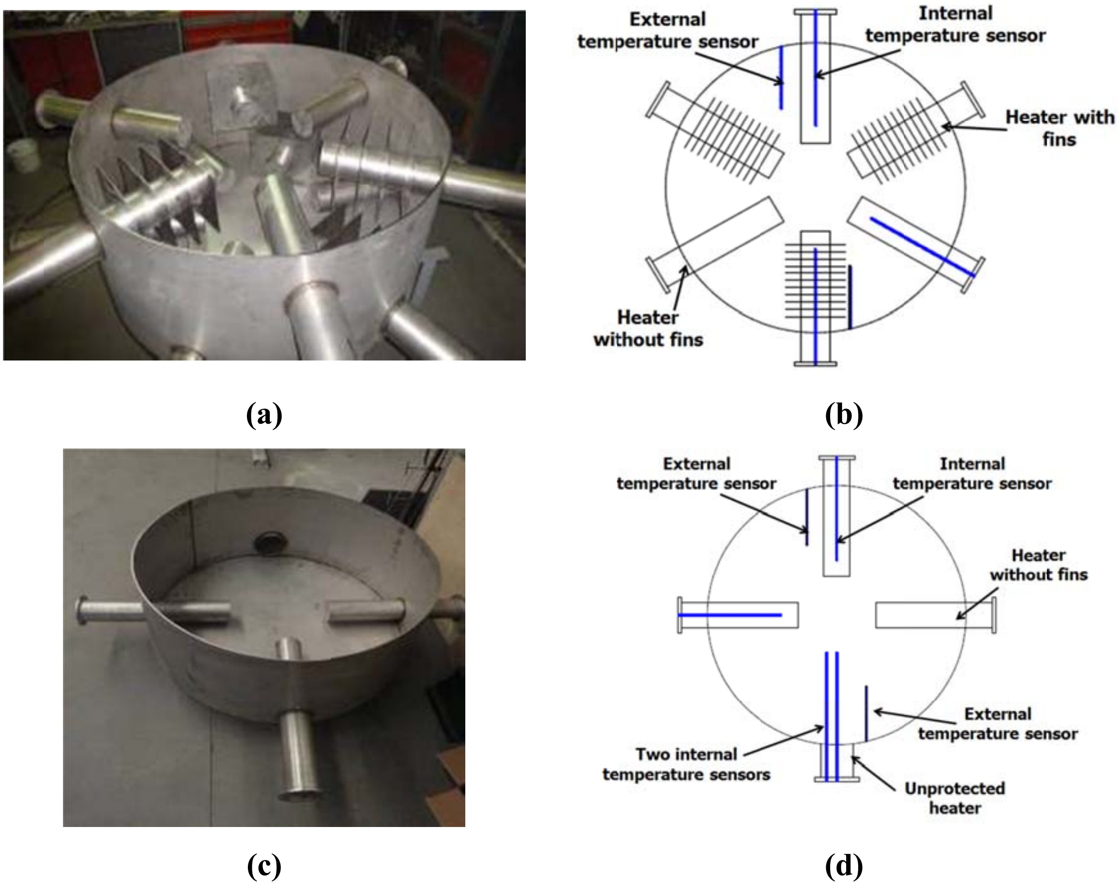


Figure 8. Immersed electrical resistances configuration. (a) Overview of the cold tank with the protective sheaths; (b) Scheme of the cold tank configuration of control; (c) Overview of the hot tank; and (d) Scheme of the hot tank configuration of control.

(a) **(b)**

Figure 9. Types of immersed electrical resistances located at the pilot plant facility. (a) Unprotected; and (b) Protected with a metallic sheath.

2.7. Measuring devices

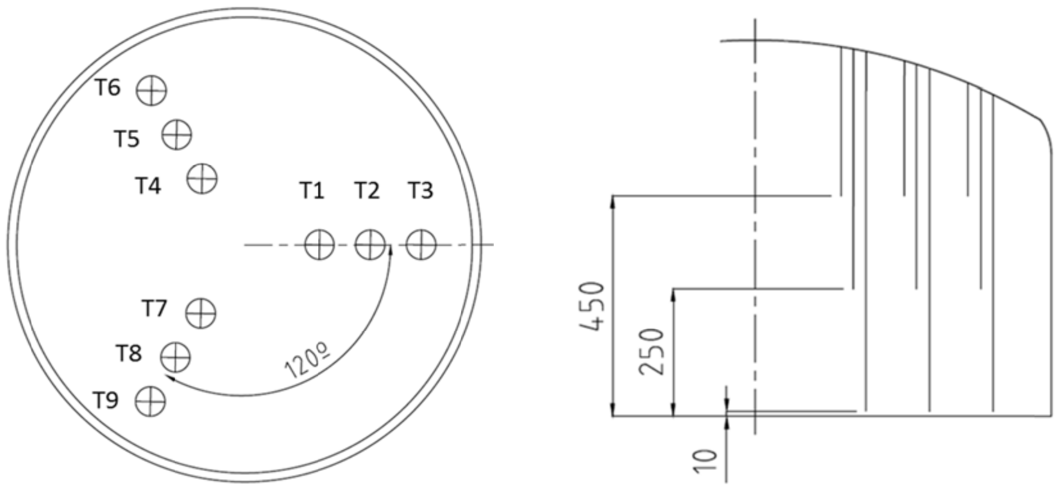
2.7.1. Molten salts level sensors

Two different level sensors are used to determine the level of the molten salts inside the storage tanks and therefore to determine the molten salts flow rate. A guided wave radar level transmitter based on a microwave guided system commercialized by Endress-Hauser, model FMR230-A2MCMJAA2A, which is placed at the cover of the cold tank, and a visual level based on a mechanic system integrated by a float and a visual system supplied by ELION, which is placed at the cover of the hot tank.

2.7.2. Temperature sensors

In order to know the molten salts temperature distribution within the storage tanks, twenty-seven Pt-100 temperature sensors with an accuracy of ±0.1 ºC are placed in each tank in nine groups of three sensors [22]. They are distributed in three different levels (at 10, 250 and 450 mm from the bottom of the tank) and in three branches separated 120 ºC (Figure 10). Moreover, to evaluate the heat losses to the environment, five Pt-100 surface temperature sensors have been placed in the transition of different insulating materials. On the one hand, between the storage tank wall and the rock wool and on the external surface of the rock wool, and on the other hand, between the storage tank and the refractory concrete, between the refractory concrete and the FoamGlass® and between the FoamGlass® and the ground (Figure 6).

All temperature sensors and data cables are protected with a metallic sheath and a ceramic protection to avoid losing accuracy and burning because of the high temperatures.



(a) **(b)**

Figure 10. Distribution of the temperature sensors within the storage tanks [22]: (a) radial distribution of the groups of temperature sensors; and (b) temperature sensors heights.

2.7.3. Flowmeters

Two different systems are used to measure the flow rate of both the HTF and the molten salts. On one hand, both loops incorporate orifice plate flowmeters, which consist of a calibrated orifice and a differential pressure transmitter. These flowmeters use the measured differential pressure between the both ends of the orifice plate to calculate the flow rate through Bernoulli equation. The flowmeter represent an innovative system, since molten salts flow rates are usually measured with NaK pressure sensors. However this system is strongly dependent on the value of the differential pressure and the proper operation of the pressure sensors, which are placed at both ends of the orifice plate. As shown in section 4.2.5, these sensors present some technical problems when operating with molten salts due to the salts solidification in their membranes which causes erroneous readings of the pressure sensors. In consequence the data obtained by the NaK pressure sensors can not to be used to calculate de molten salts flow rate.

On the other hand, due to bad operation the orifice plate flowmeter and the fact that this system can only work in one direction, the molten salts flow rate is calculated from the values obtained with the level sensors and using a homemade device which consists of a metallic tube that measures the molten salts level variation inside the tank during a fixed time interval.

2.7.4. Pressure sensors

In order to measure pressure values of both the HTF and the molten salts at different points of the two loops, different types of pressure sensors are used. On one hand, the HTF loop incorporates three mechanical manometers and five digital pressure transmitters. The mechanical manometers are installed at the inlet and outlet of the heating system and at the expansion vessel. The first ones are used to visually know the pressure drop within the electrical heater while the third one is used to visually control the HTF thermal expansion. Three of the digital pressure transmitters are installed at the same locations than the mechanical manometers and are used to record and control the pressure variables of the HTF loop. The two other digital pressure transmitters are installed at the inlet and outlet of the heat exchange system to record and control the pressure drop of the HTF within the heat exchanger. On the other hand, the molten salts loop incorporates three bellow-type pressure sensors with digital pressure transmitters. One of them is located at the inlet part of the heat exchanger to know the pressure of the nitrogen at heat exchange system and the other two sensors are placed at both ends of the orifice plate flowmeter.

3. Operational modes of the pilot plant facility

The pilot plant facility presented in this paper allows simulating charging and discharging processes of commercial two-tank molten salts TES systems with both parallel and counter flow arrangements (Figure 11). In a parallel flow arrangement (Figure 11a Figure 11c), the hot fluid and the cold fluid move in the same direction, while in a counter flow arrangement (Figure 11b Figure 11d), the hot fluid and the cold fluid move in the opposite direction.

During the charging process (Figure 11a and Figure 11b), the molten salts are pumped from the cold tank to the hot tank through the heat exchange system. There, the molten salts are heated up with the HTF which has been previously heated up with heating system. The charging process is considered to be finished when the level of the molten salts at the cold tank reaches the lowest level for a proper performance of the molten salts pump, which turns to be 23 cm from the bottom of the tank. On the contrary, during the discharging process (Figure 11c and Figure 11d) the molten salts are pumped from the hot tank to the cold tank through heat exchange system.

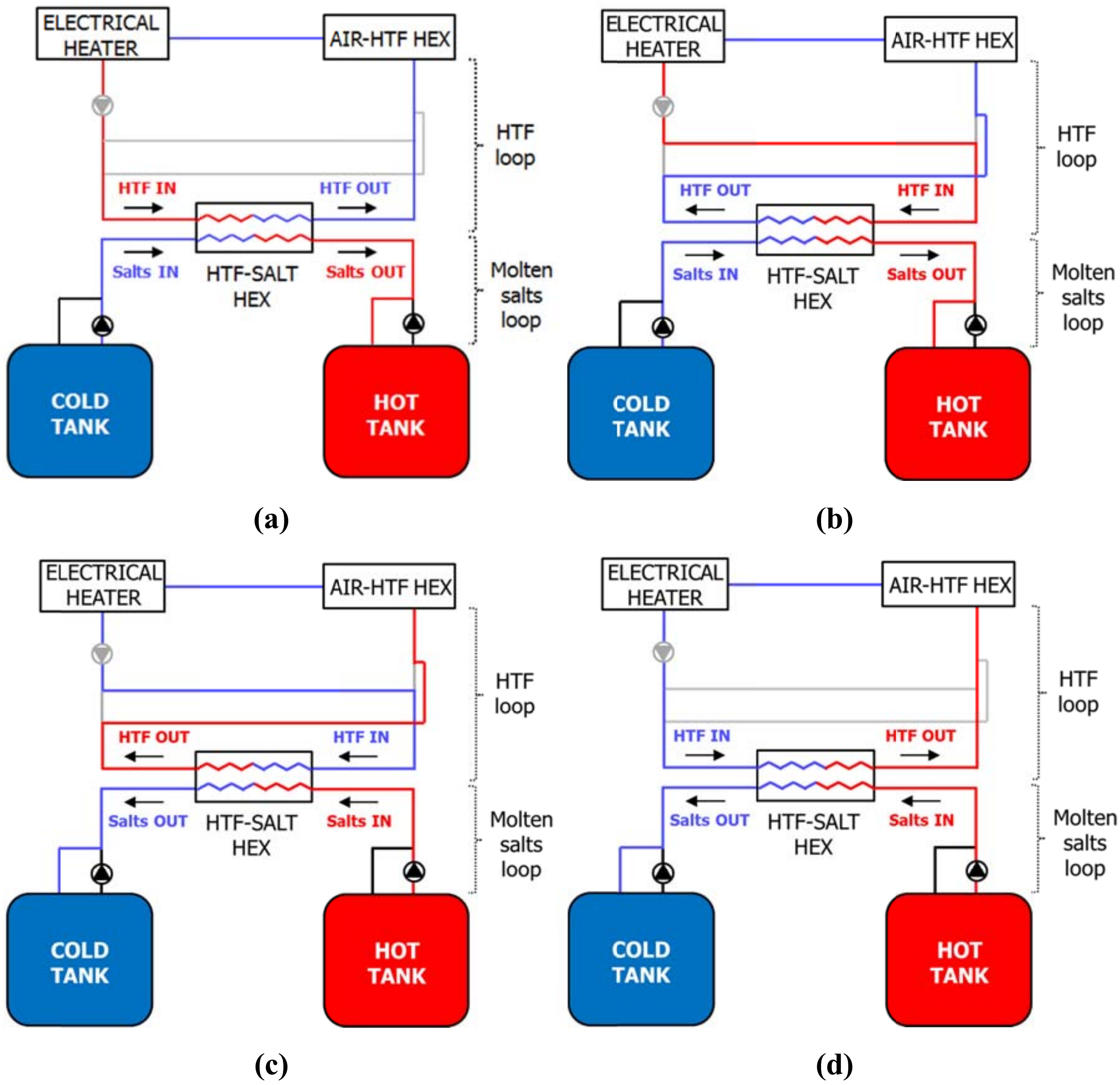


Figure 11. Operational modes of the pilot plant facility [23]. (a) Charging process in parallel flow; (b) Charging process in counter flow; (c) Discharging process in parallel flow; and (d) Discharging process in counter flow.

4. Start-up and operation: Procedure performed and recommendations for future experimental pilot plant facilities

One of the most critical phases before starting the experimentation in a pilot plant facility is its start-up. The objective of this section is to explain the procedure performed at the University of Lleida and to give recommendations for an optimal start-up and operation of future testing pilot plants.

4.1. Start-up

4.1.1. HTF loop

The following steps need to be followed for the start-up of the HTF loop:

i. The first step is to fill the HTF loop with pressurized air to check the proper operation of the pressure and temperature sensors, and to check the absence of leaks in the circuit, which is done verifying that there are no air pressure drops.
ii. The second step is to fill up the HTF loop with the selected HTF. In the present facility, it was done by pumping the whole volume of HTF with a manual pump from the lowest point of installation, so the existing air in the piping could be drained by the relief valve.
iii. The third step is to introduce nitrogen through the HTF expansion vessel to reach the minimum heating system working pressure, and therefore to be able to pump the HTF at ambient temperature at different flow rates, which will let the remaining air to be drained.
iv. Once it is verified that the HTF loop has no presence of air, a dehumidification process needs to be carried out to eliminate the moisture in the loop. This process consists of a progressive increasing of the HTF temperature, 5 ºC every 5 minutes until it reaches 170 ºC. Afterwards, the HTF is kept at this temperature for a whole day to be further cooled down to 50 ºC.
v. Finally, when the dehumidification process is successfully done, the HTF need to be gradually heated up to its maximum working temperature to calibrate the control system and the alarms of the heating system.

4.1.2. Molten salts loop

The following steps need to be followed for the start-up of the molten salts loop:

i. The first step is to check that there are no leaks and to check the correct operation of the temperature and pressure sensors by introducing nitrogen in the storage tanks and piping, which is done in the same way than in the HTF loop.
ii. After verifying the absence of leaks, the next step is the installation of the electrical tracing system and insulation.
iii. Afterwards, and once it is checked that the electrical tracing system operates properly, both the tracing and the resistances need to be set at 280 ºC to ensure an initial preheating temperature for the molten salts at the piping. This temperature is the set-

point in real CSP plants to ensure that the molten salts do not solidify. Once this temperature is reached, it is possible to fill up the storage tanks with the molten salts. In the present facility, the biggest amount of material was introduced in the cold tank to take advantage of the presence of more electric resistances that the other one.

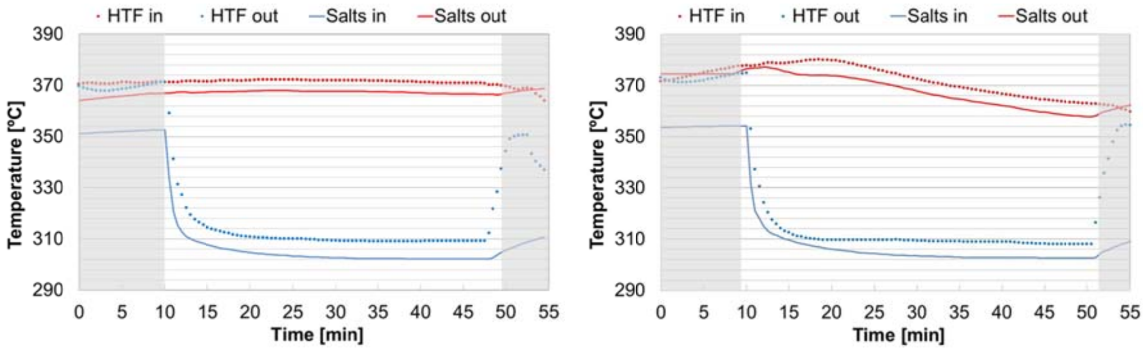
Unlike commercial CSP plants, where the molten salts melting during the filling process is carried out by an external system, in the present facility the melting process was carried out for the first time inside the storage tanks with the heat transferred by the electrical resistances. The process consisted of progressively increasing the molten salts temperature, with temperature gradients below 50 ºC to avoid the thermal stress of the storage system, until it reached 250 ºC. Once the molten salts were fully melted, the temperature was increased up to the working temperatures (298 ºC at the cold tank and 388 ºC at the hot tank) and they were pumped to perform the charging and discharging processes.

4.2. Main issues during operation and recommendations

4.2.1. HTF loop

The main issues detected in the HTF loop during operation are the presence of air and vapours in the piping and the presence of HTF leakages. These problems are key factors on keeping the required minimum HTF level of the pump, keeping the proper pressure in expansion vessel, and avoiding the cavitation of the pump. The presence of air is basically due to human manipulations on the piping and valves. In order to avoid or minimize this problem, the present facility incorporates two drainages, which are located at the highest point of the HTF loop and at the HTF pump, and that are able to relief the accumulated air. The presence of vapours is due to values of the HTF pressure in the expansion vessel which are lower than the HTF vapour pressure. In order to avoid it, it is necessary to keep the pressure of the HTF loop always higher than the HTF vapour pressure, especially at high temperatures. Finally, HTF leakages were mainly due to poor connections in critical points such as metallic flanges, pipe joins, and instrumentation fitting. In order to avoid leakages for large periods of time at high pressures and temperatures, the use of spiro-metallic gaskets between the flanges and pipe joints, as well as a constant revision of the instrumentation fitting have been found as a good solution.

Figure 12a shows a good characteristic behaviour of a charging process in the HTF–salts heat exchanger and Figure 12b shows a problem in the HTF loop with a decrease of the HTF inlet temperature.



(a) **(b)**

Figure 12. (a) Good behaviour of the charging process in the HTF-Salts heat exchanger; and (b) Bad behaviour in the HTF loop.

4.2.2. Molten salts loop, heat exchange system and storage system

The two main problems which are usually found in the molten salts loop, the heat exchange system, and the storage system are the molten salts leakage on the connection points and the molten salts solidification. The first issue is usually avoided by either welding these connections or using spiro-metallic joints, as well as with a continuous checking of the sealing of valves and instrumentation. The second issued appears as a result of the heat losses to the surroundings and to the support structures, and causes plugs in the pipes, a blockage on the rotational axis of the pump, and occasionally shutdowns of the pilot plant facility. A combination of a well-designed electrical heat tracing system, a proper insulation, and a constant check of the thermal bridges with a thermographic camera is recommended to avoid this problem.

4.2.3. Insulation

The insulation tends to deteriorate as a result of a prolonged exposure to high temperatures, which modifies the insulation appearance by darkening. This deterioration makes the facility to have a worse performance and increases the risk of fire. Moreover, the impregnation of the insulation due to molten salts and HTF leakages increase these problems. In order to avoid that, it is recommended to constantly check the most likely points to leak and to renovate the insulation as recommended by the supplier. Figure 13a shows a the appearance of a burned insulation and Figure 13b shows the insulation with salts due to a salts leak in the valve.

(a) **(b)**

Figure 13. Appearance of damaged insulation: (a) Burned insulation; and (b) Insulation impregnated with salts due to a salt leakage in a valve.

4.2.4. Electrical heat tracing

The electrical heat tracing is a key system for the optimal performance of the experimental set-up. During its installation, it is important to properly place it along the piping either in spiral form or at both laterals of the pipe to ensure a good heat transfer along the pipe and to achieve a homogeneous distribution of temperature. This configuration helps to prevent possible burning and solidification of salts inside the piping. Moreover, potential thermal bridges such as valves should be covered with a metallic mesh which needs to be connected to the electrical heat tracing as explained in Section 2.6.1.

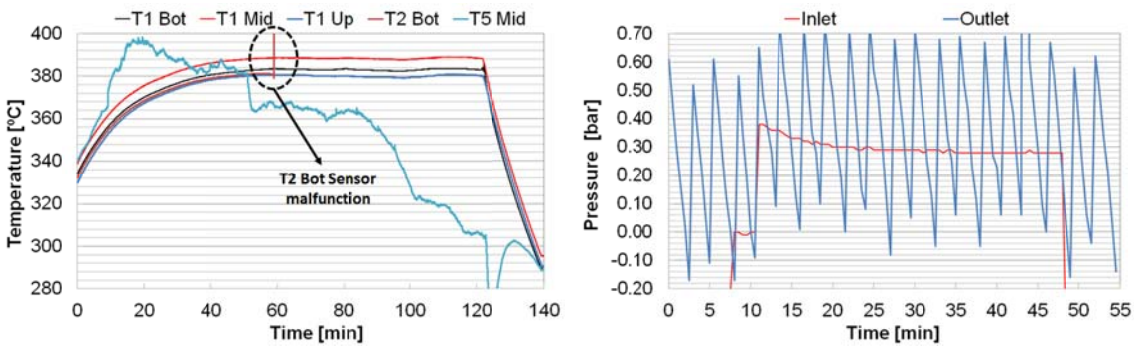
Another problem with the electrical heat tracing is the reduction of its wire electrical insulation due to a poor manipulation or a poor sealing at the cold ends. It causes a reduction on the resistance of the wire housing and therefore either a breakdown of the wire or a malfunction. Hence, it is important to provide a good sealing and to perform a good manipulation during the installation of the heat tracing to avoid the chipping of the electric wire.

4.2.5. Measuring devices

The most important parameters to take into account with temperature sensors during operation are their location and length. Temperature sensors should be installed far away from bifurcations or flow disturbance elements to ensure a developed flow and to avoid the influence of their thermal inertia. The sensor signal wire has to be protected with a metallic resort, which should have a length slightly longer than the thickness of the insulation, to avoid its burning as a consequence of high temperatures. Figure 14a presents the consequence of the above-mentioned problems in a temperature profile of five temperature sensors located inside hot tank. While the sensors named "*T1 Bot*", "*T1 Mid*", and "T1 Up" show a correct behaviour for a fixed temperature set-point of 380 ºC, sensors named "*T5 Mid*" and "*T2 Bot*" show an undesired behaviour. Sensor named "*T5 Mid*" presents a fluctuation on the temperature profile in steady state period due to interferences in signal caused by radar level which is installed near the sensor, and sensor named "*T2 Bot*" stops giving data after minute 60 due to the burning of the sensor signal wire.

Regarding the pressure sensors, the molten salts bellow-type pressure sensors present problems due to salts solidifications in their membrane. It has been observed that due to this problem, this type of sensor is currently not recommended for working with molten salts. Figure 14b shows the pressure profile of the sensors located at inlet and outlet of heat exchange system during a charging process. As it can be seen, the inlet sensor has a constant value of pressure during the steady state of charging process while the outlet sensor presents an undesired oscillation due to solidifications.

Finally, some important cautions should be taken into account regarding the level sensors. The radar level sensor should be installed far away from obstacles, such as sensors, electric resistances and the pump, which highly affect the distribution of the waves of the radar and therefore the level reading. This sensor is also very sensitive to disturbances such as vibrations. The mechanical level sensor should be installed far away from the pump to diminish the contact with the molten salts drops which splashes during salts recirculation. If these liquid molten salts drops solidify inside the sensor, it can block the float of the meter and affect the measurement.



(a) **(b)**

Figure 14. (a) Example of good and bad behaviour of temperature sensor inside hot tank; and (b) Example of good and bad operation of salts pressure sensors in heat exchanger.

5. Conclusions

This paper presents the acquired experience during the design, start-up and ordinary operation since 2008 of two-tank molten salts TES for CSP applications pilot plant scale built at the University of Lleida (Spain) in conjunction with Abengoa (Spain). This test facility is used to experimentally investigate different materials, components and operational strategies regarding TES at a temperature up to 400 ºC.

The authors show the problems and limitations encountered, and give advices of this experimental set-up to extrapolate the data to real plant, to provide solutions to technical problems and reduce the cost of commercial plants.

One of the points to be exposed is that many items or components of the pilot plant were designed and/or built specifically for this set up, since they are not standardized. Moreover, some instrumentation was tested in this application for the first time in this pilot plant.

Pilot plants should always be designed taking into account the scalability of its results. The results obtained in a pilot plant do not always have the same impact in a real commercial plant. For example, heat losses in a pilot plant such as the one presented in this paper will have a mucho lower impact than in a commercial plant. Contrary, this plant shows lower stratification than commercial ones.

In the start-up process two conclusions are drawn. The first one is an expected one, the first heating should be done progressively to avoid thermal stress in the container metals and to avoid presence of air and HTF vapours. The second one is that it is possible to melt the salts just with the immersion heaters, which was not expected and had not been tested before in bigger plants.

To avoid malfunctions found in the pilot plant, the following recommendations, which can be extrapolated to commercial plants, can be given: leaks and salts solidification in cold points are the main problems in the HTF-salts circuit; a good installation of the electrical heat tracing and insulation is a key factor for the proper operation of these plants, especially in low-scale plants as the one described because they have many disadvantages derived of its scale factor, for example more heat losses and less thermal inertia in the piping. Also there is a need to protect the signal wires against disturbances and high temperatures; radar level meters are extremely sensitive to disturbances; it is important to avoid the presence of salts inside any mechanical level meter; bellow-type pressure sensors are not good for salts; and plate orifice flowmeters can be a good and accurate solution with good pressure sensors.

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