Design and Construction of Molten Salt Parabolic Trough HPS Project in Évora, Portugal

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Abstract

In the Portuguese city of Évora a parabolic salt loop is being constructed in order to demonstrate the viability of this system. Different partners have teamed-up for this task. Siemens takes the project lead in the German HPS consortium. The solar demonstration plant will be capable to produce high live steam parameters in an once-through steam generation system (SGS). The SGS is designed for 580 °C and 140 bar. The live steam parameters and the design of the SGS and the overall plant provide a highly flexible steam production.

Since the solar field needs to provide heat at higher temperatures than typical solar field set-ups and uses molten salt as heat transfer fluid, different adoptions have had to be made. Several of these adoptions are described in the paper. Furthermore the layout of the flexible connections consisting of hose and rotary must be re-designed. Targets of the developments are: both thermal expansion of the absorber pipe and rotation of SCA must be compensated for reasonable number of lifetime cylcles and the complete system must be designed in order to prevent any freezing of the salt within the component.

1. Introduction

Molten Salt as alternative heat transfer media for parabolic trough systems shows a potential for lowering the levelized cost of electricity (LCoE). Kearney et al [1] described that a reduction of LCoE greater than 10 % depending on the salt mixture is possible. Turchi et al [2] approved the LCoE reduction potential, as he published reductions of 6 to 15 % depending on different solar field sizes. In [3] the influence on storage size, high and low process temperatures and employed salt have been assessed, it was demonstrated that further optimization potential can lead to further LCoE reductions.

Beside the economic advantages the molten salt technology comprises further advantages. The decomposition temperature of NaK-NO3 salts - as demonstrated in Solar Two-Project [4] - is above 550 °C, thus, more than 150 K higher than applied state-of-the-art thermal oils. This leads to higher system efficiencies of the power block due to a rise in higher steam parameters, both pressure and temperature. Furthermore the thermal energy storage can be built smaller and due to this higher efficiency, considerable reductions of costs will be able to be realized. This provides again a potential to a significant lowering of LCoE by adding huge storage systems [5] and increasing the capacity factor, respectively. In a mid-term view, where storage comes more and more into focus when integrating renewable energy into the power grid, this will be of high importance. Due to the direct storage of the thermal energy the heat collection and the power production can be fully decoupled, so the demand of the grid operator can be comprehensively fulfilled. Last but not least, molten salt is not soil-permeable and therefore it is not environmentally harmful to ground water.

There are currently demonstration plants of molten salt being in operation or being under construction. In Italy the Archimede Project was first in taking efforts on molten salt parabolic trough technology [6]. In order to demonstrate the feasibility of utilizing molten salt as the heat transfer fluid and for thermal storage in a parabolic trough solar field (SF) a second European demonstration plant in Évora, Portugal is being engineered, procured and constructed. It consists of one loop of parabolic trough collectors summing up to a total irradiated length of 600 m. The thermal energy storage (TES) system thermally disconnects the solar loop from the steam generating system (SGS) for providing a solar-independent steam production. The SGS is able to provide live steam parameters of 560-580 °C / 140 bar by a single path once-through boiler design. The water-steam cycle is equipped with throttling equipment in order to simulate different steam turbine behaviors and allow the demonstration of sliding pressure operation in the subcritical Benson-type boiler.

It is targeted to demonstrate the technical the viability of the system and its components. It will be possible to determine optimized operating parameters and, thus, achieving further cost reductions for a better competitiveness of parabolic trough systems.

1.1 EPC Partners

For the development, design, engineering, erection and commissioning of the HPS Evorá Test Loop a team has lined-up under the co-funding of the German Ministry for the Environment, Nature Conservation and Nuclear Safety. The team working on components, engineering and erection of the test loop are Siemens Energy, DLR, Steinmüller engineering and senior flexonics.

Siemens AG develops, manufactures, integrates and installs concentrated solar power equipment and solutions in the entire world and is the only company that can provide solar power generation to transmission and distribution solutions and products, in all its multifaceted. For Siemens AG, the Test Loop in Évora is decisive and constitutes the first step for a future Test-Platform where develop further R&D programs and technologies. For this reason, Siemens AG is in charge of the coordination, development, erection and commissioning of the Test Loop and the HPS program.

DLR is working on concentrated solar power since the 80ies. The Institute of Solar Research is spread over four locations – Stuttgart, Cologne, Almería in Spain and, recently, Julich. DLR supports the team with the set-up of the process, definition of instrumentation, support the commissioning phase, definition of test plans and procedures and co-run the test facility.

Steinmüller Engineering GmbH, a follow – up of the L&C Steinmüller company, is a supplier for steam generators in pressure vessels. Typical applications are waste heat boilers for chemical processes with high pressures and temperatures. Steinmüller already started in the 90ies with tests for solar power generation in Almería. For the presented projects, Steinmüller supports the complete water steam cycle of the test loop with engineering and hardware supply.

Senior Flexonics GmbH is involved on CSP since the first commercial solar power plants in the 80ies. Senior Flexonics offer an extensive spectrum in the area of renewable energies: the products are weather resistant and can withstand enormous pressures and temperatures as well as mechanical stress due motion. All products are designed for a maximum life span and the highest safety. The products have been used in all areas of CSP applications for decades. With Senior Flexonics' know-how and experience from many years in the market for the solar power generation, they are responsible to develop and manufacture the flexible solution between the HCE tube and the connecting pipe.

2. Location and Set-up of the Molten Salt Test Loop

The Évora HPS Molten Salt Test Loop is located in Portugal about 100 km south-east to Lisbon. In Évora a university is located whereby the Test Loop is currently being constructed, see figure 1 (left). The geographical location is 38°31' N, 8°0'W.

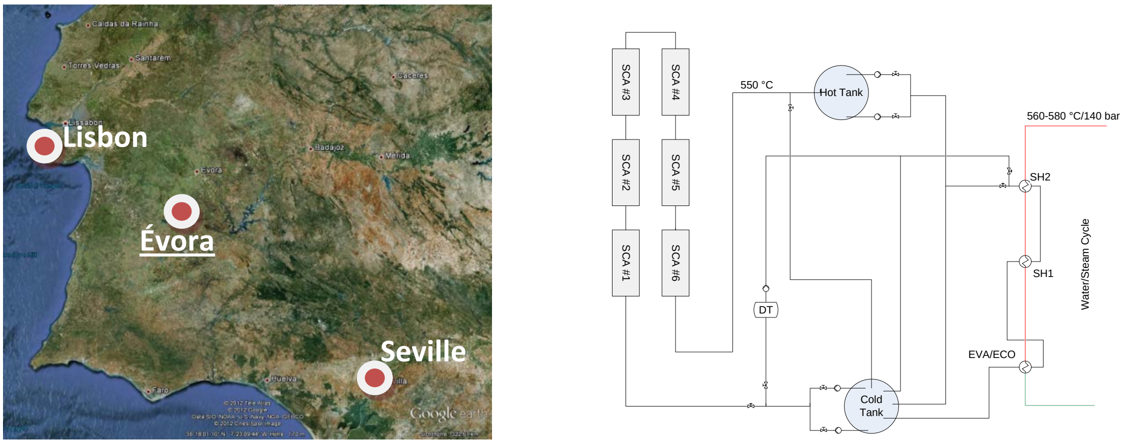

Fig. 1: Location (left) and simplified salt layout of the HPS Test Loop (right)

The solar field consists of six Siemens SunField-6 solar collectors (SCA), each having an irradiated length of approx. 100 m and an aperture length of 5.66 m, see figure 1 (right). The molten salt is then conducted to the thermal energy storage system consisting of two separate tanks. The collected hot salt can be directed to the steam generating system. There the energy is transferred to the water/steam-cycle heating up water to maximum live steam parameters of 560 °C/140 bar. The demo loop is not equipped with a steam turbine since it is not proposed to generate electricity but to be a scientific basis for research activities in molten salt systems and once-through type boilers. Thus, the live steam pressure is controlled by a set of throttles and cooled down by a condenser. Furthermore, an additional salt tank is integrated. It is located below the ground in order to provide the possibility to drain the system geodetically. The current state of the construction site is shown in Fig. 2.

Fig. 2: Panoramic view of current status of the construction site. On the left hand side the solar loop will be erected. The drainage tank is shown on the lower center, the two storage tanks are show on the right hand side and the two blue skids contain the SGS and the water cycle

The Test Loop is designed to test different salt candidates; these are all nitrate salts like Solar Salt which are currently well known. The further mixtures contain for example calcium or lithium. In the ongoing project different salts will be tested in order to gain experience in handling of the salts and its process. Furthermore it allows identifying the most suitable salt mixture for application in parabolic trough plants.

3. Process and Thermodynamic Design of the Test Loop

The plant as shown in Fig. 1 has three major components: solar field, thermal storage and steam generating system. The solar field is the heat source of the system; its main operating modes are:

- Start-up of the system
  The cold solar field will be heated up by the solar irradiation until the stationary temperature profile in the loop is reached. The salt will in this mode be circulated over the cold tank
- Normal operation
  The solar field will be controlled to maintain the desired outlet temperature. The salt flow is now directed to the hot salt tanks
- Shut-down of the system
  While still circulating the salt, the solar field will be set to its stow position. The energy stored in the steel masses will be transported to the storage tanks.
- Anti-Freeze Protection
  During night (and overcast) times the salt will be circulated in the solar field so that in no position of the fluid path the temperature falls below a certain minimum temperature

The steam generating system is the heat sink for the salt. The main operating modes are very similar to the solar field:

- Start-Up of the steam generator system
  A temperature and flow gradient will be applied at the SGS in order to rise the pressure and temperature of the live steam to its desired parameters.
- Normal operation
  Like in a conventional plant the energy output is set and the heat flow to the SGS follows the demand. Thus, the salt feeding parameters are determined by the steam generator.
- Shut-down of the steam generator system
  According to the needs of the SGS the feeding salt mass flow and temperature is lowered. When the temperature of the cold tank is reached the shut-down is finished
- Night Operation
  Salt will be circulated in the shell-side of the SGS to prevent any cold spot.

The process of the demonstration plant is designed that any SF and SGS operating modes can be run fully independently. The solar heat input is fully decoupled from the steam generator allowing a fully flexible plant operation.

3.1. Solar Field

The inlet operating temperature is set to 290 °C. The receiver temperature can be raised to 580 °C. The nominal operating fluid temperatures will be 550 °C. Under design meteorological conditions the Archimede HCEMS11-Receivers [7] will transfer more than 1.7 MW_t of thermal power to the molten salt; resulting in a salt mass flow of 4.3 kg/s and a total pressure loss of less than 2 bar in the solar loop.

Since not all nitrate salt mixtures are capable to run at temperatures of up to 550 °C, the system is designed to be able to run lower outlet temperatures as well. Since heat capacity and density of the nitrate salts are quite similar, the fluid velocity alters strongly by the outlet temperatures. So, for example, higher pressures and pumping power is needed. The system is designed to allow lowest temperatures of around 400 °C. So the full range from the state-of-the-art temperatures levels of current systems to maximum temperatures of 580 °C can be demonstrated.

The solar field is the new retrofitted Siemens SunField-6.1 and is equipped with Archimede HCEMS11-Receivers and flexible connections by Senior Flexonics. In order to fully qualify the thermal and optical properties of the entire systems is highly instrumented. The solar field instrumentation comprises 25 fix temperature measurements and one flow meter. During commissioning and test phase further temporary instrumentation will be applied and different measurement methodology will be conducted, like Q-Fly [8].

3.2 Thermal Energy Storage and Drainage Tank

The design of the TES system fulfills three main objectives: first, storing hot molten salt in order to extend time of steam generation. Second, storing the salt to provide sufficient energy needed for the nightly anti-freeze operation of the solar field and steam generating system. Probably the most interesting point of the TES in conjunction with the used once-through boiler type is the demonstration of total dispatchability of steam production as well as the ability of such a configuration to participate in the secondary control. This will be a unique characteristic for solar thermal power plants and a break-through for STE systems to gain competitiveness against renewable energy forms like wind and PV. Both tanks are designed to be capable of holding the entire salt inventory of the entire system. The initially introduced Solar Salt will have a total mass of 56 tons.

Each tank is equipped with 48 temperature measurements. For a full qualification and understanding of the thermal and structural behavior of the storage tank the measurements are located inside the tank, on the tank surface and in the foundation of the tank. Furthermore, each of the big storage tanks is set-up with two redundant pumps for a secure operation. The pumps are fully flexible from zero to maximum mass flow and can be controlled by throttling and/or frequency control.

The drainage tank is located at the lowest point of the plant and is able to take the salt content of the solar field, the steam generating system and the complete piping of the system.

3.3. Steam Generating System and Water-Steam Cycle

The task of the SGS is to produce high quality live steam by cooling down the hot molten salt from the solar field and/or the hot salt tank. In cooperation with project partners, Steinmüller Engineering decided to develop a once – through type steam generator system, see Fig. 3.

Fig. 3: Steam generating system (skid on the right side) and water cycle (skid on the left side) with high live steam design parameters of 580 °C and 140 bar

The once – through type steam generator allows

- steam parameters up to 580 °C/140 bar
- steep startup temperature gradients of about 15 K/min
- real sliding pressure operation within the range of 70 – 140 bar
- flexible operation in range of 33 – 120 % load

The thermal duty during nominal operation equals 1780 kW @ 100 % load.

Besides the demanding steam parameters, the mechanical design of the steam generator had to be done with respect to the physical behavior and properties of the molten salt mixture. In particular, the high specific energy content leads to low velocities of the heat transfer fluid, a small pitch and low tolerances caused challenging conditions for the manufacturing process. To ensure a proper drainage of the molten salt, no dead ends are allowed and a sufficient slope had to be established in any case. The design needs to be fail - safe concerning the black out of any pump or regulating device. Possible freezing shall be prevented not only inside the vessels but also in any valve and related pipework.

Due to the lack of a turbine, the superheated steam will be throttled and cooled down by water injection to 5 bar saturated steam. Downstream this simulated turbine the steam condensates in an air cooled heat exchanger. The condensate is collected at 5 bar pressure inside a pressure vessel and pumped back to the feedwater tank.

The feedwater tank is operated with boiler feed water at 55 bar / 270 °C. A portion of superheated steam is injected to control temperature / pressure inside the tank. This measure, in combination with an electrical startup heater, ensures a constant inlet temperature of 270 °C at the economizer section of the steam generator and provides the molten salt from freezing.

4. Development and Re-Design of Equipment for Salt Application

4.1 Re-Design of the Siemens SunField-6 Collector

In order to be able to compensate the higher thermal expansion due to higher operation temperatures in comparison to oil applications the SolarField-6 (SF6) Collector has been re-designed for molten salt application; resulting in good optical performance of the loop even at higher operating temperatures. Furthermore now the SF6 collector is enhanced so that impedance heating can be applied, which allows transferring heat to the molten salt during emergency situations in order to avoid solidification.

The following adaptions have been made:

- Adjustment of the collector’s structure due the heavier Molten Salt
- Adjustment of HCE supports due the higher thermal expansion and the need of an impedance heating insulation
- Full horizontal alignment of field and new drainage concept
- Implementation of new flexible connections

4.2 Flexible Connection for Molten Salt Application

The connections at the ends and between the SCAs are realized by flexible hose systems. They are designed to compensate the thermal expansion of the Archimede absorber pipes and the rotation of the SCAs at high operational temperatures of the molten salt. In order to achieve a robust and secure operation of the flexible hose systems its design is adopted to allow impedance heating of the flexible hose systems when necessary in order to avoid freezing of the liquid salt.

The approval of the feasibility of all components, parallel to the fabrication is the key development task of Senior Flexonics.

An alternative solution which is consisting of a combination of stainless steel hose only is analyzed as well to prepare an alternative path in case that the developed rotary will show different performance results and will be not consistent enough for the given media.

The main development points are:

- obtain more than 3000 rotation cycles
  - with the expansion performing component
  - with the rotation performing component
- guarantee the impedance heating (using the best material ratio over the whole system)

The preliminary internal tests in our in house laboratory are concentrated to evaluate the reliable use of the different components, the internal tests are carried out with two methods:

With molten salt

1. In an oven we are heating the rotary which is filled with salt up to 500°C
2. Pressurizing the system with 25 bar
3. Rotating the component under the mentioned conditions

The tested component is the rotary

Mechanical test

1. The complete system
2. In our 1:1 scale test rig
3. Under ambient temperature
4. Rotating the component and movement of the expansion

The tested components are the:

- Stainless steel hose
- Rotary

The internal in house testing has delivered variances in the results and are currently generated with the rotary. Tolerances and material behavior of the housing and the different rotary components are currently under examination to understand the influence of the various elements.

The alternative path is the mentioned complete stainless steel hose solution to guarantee the explained technical properties.

Currently the in house tests are analyzing the best installation points and trying to stay as close as possible to the original proposed installation points. First results have delivered slightly changes to the given installation points which have to verified with the main design of all the molten salt transporting tubing.

4.3. Once-Through Salt-to-Steam Steam Generating System

The SGS is designed according to ASME VIII-1 standard. The once-through design of the SGS consists of one economizer/evaporator, a separator and two serial superheaters. Salt in the heat exchangers is located always on the shell-side and water within the tubes of the heating surfaces. This allows higher steam quality and due to the characteristics of a once-through boiler, never before achieved start-up times, load changes and flexibility in steam production. Furthermore, the SGS is the first step to a supercritical steam production process. This will open the door to new applications, higher efficiency and boost the general acceptance of the STE due to its ability to not only participate in the day-ahead electricity market, but also to provide dispatchable energy and of even more interest, to have the ability to stabilize the grid due to its swift controllability of load changes. Comparable load gradients are achievable at the time by gas turbines only.

5. Test procedures

There are different test procedures to be run. Whereas at the demonstration loop the test will focus mainly on the overall performance of each system – solar field, thermal energy storage and steam generating system. The components will prior to its installation being tested in the laboratories of the partners. The laboratory test procedures of the flexible connections are already described in Section 4.2.

In Evora's demonstration loop the main targets of the test phase are

- Demonstration of full functionality of plant under all conditions
- Demonstration of fully automated operating modes as described above
- Determination of most feasible blackout concept (not described in that paper)
- Demonstration of full drainage by different approaches (not described in that paper)
- Identification of optimized process parameters
- Determination of the most economic overall plant design

6. Conclusions & Outlook

The current status at the site in Evora can be seen in Fig. 2. All main components are at the construction site. The steam generator, superheaters and related equipment are mounted on one skid, the auxiliary equipment on a second one. Both skids have been designed, manufactured and shipped to location after successful pressure test. The two thermal storages and the drainage tank are on site and already fully equipped with its instruments. The flexible hoses are currently being analyzed in laboratory tests for determine the best installation points. The commissioning phase will start with the beginning April 2013: cold commissioning and melting/filling process; afterwards followed by the test phase. The HPS project will end in March 2014.

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References

[1] D. Kearney, B. Kelly et al. (2004): Engineering aspects of a molten salt heat transfer fluid in a trough solar field. Energy, Volume 29, Issues 5–6, April–May 2004, Pages 861-870.

[2] Turchi, C., M. Mehos, et al. (2008): Current and future costs for parabolic trough and power tower systems in the US market. SolarPACES 2012, Perpignan, France.

[3] Wittmann M., Müller-Elvers C. et al. (2012): Optimization of Molten Salt Parabolic Trough Power Plants using different Salt Candidates. Proceedings SolarPACES 2012.

[4] Pacheco, J.E. (Ed.) (2002): Final Test and Evaluation Results from the Solar Two Project. Sandia Report SAND2002-0120.

[5] Turchi, C., M. Mehos, et al. (2008). Current and future costs for Parabolic Trough and Power Tower Systems in the US market. SolarPACES 2011, Perpignan, France.

[6] Falchetta, M., D. Mazzei, et al. (2009). Design of the Archimede 5MW molten salt parabolic trough solar plant. SolarPaces 2009. Berlin.

[7] HEMS11. Archimede Solar Receiver Tube for Thermodynamic Power Plant Technical Data. Archimede Solar Energy. <http://www.archimedesolarenergy.com>.

[8] Prahl, C., B. Stanicki et al. (2011) Airborn Shape Measurement of Parabolic Trough Collector Fields, SolarPACES 2011, Perpignan, France