Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 49 (2014) 956 – 964

Energy Procedia

SolarPACES 2013

CFD model of a molten salt tank with integrated steam generator

E. Rivas*[1], E. Rojas[1], R. Bayón[1], W. Gaggioli[2], L. Rinaldi[2], F. Fabrizi[2]

[1]*CSSU-Thermal Storage-CIEMAT-PSA, Av. Complutense 40, 28040 Madrid (Spain)*
[2]*UTRINN-STD, ENEA, Casaccia (Italy)*

Abstract

For each solar technology the dispatchable CSP plant scheme that maximizes the solar to electrical energy conversion and minimizes the costs associated to such transformation is searched. In recent years double tank TES systems are evolving towards more simple configurations of a single tank [1], [2], [3], also known as thermocline tank TES systems and, even going beyond, there are already thermocline tanks in process of development where the steam generator (SG) is integrated into the storage tank (European project OPTS).

A prototype with integrated SG has been erected for testing purpose in the Casaccia Research Centre of ENEA (Italy) [4]. The model presented in this paper reproduces the experimental data of such prototype using the CFD commercial code STAR-CCM + [5].

Unlike very few published until now [6]. The simulated system account for molten salts behavior, not only for the bulk molten salts, but also for the circulation of the molten salts inside the SG (with three steam coils). The molten salts move by induced natural convection and the steam temperatures and pressures are up to ~500º C/40bar. Temperature gauges situated in the bulk and the molten salts mass flow inside the SG are the main variables considered for validating the model. From the numerical point of view is a transient simulation and the model is 2D-axisymmetric. The required features of the system mesh and the physical models used are presented in this work.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.

Keywords: sensible heat; molten salts; thermocline storage tank; CFD, integrated steam generator, induced natural convection

---

---

* Corresponding author. Tel.: +34-914962505; fax: +34-913466037.
E-mail address: esther.rivas@ciemat.es

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
doi:10.1016/j.egypro.2014.03.103

1. Introduction

The OPTS project (Optimization of a Thermal energy Storage system with integrated Steam Generator, 2011-2014), EU funded, looks for demonstrating the techno-economic viability of a new storage concept, which is based on three main points:

- The use of molten salts as heat transfer fluid & storage medium
- The use of using a single storage tank or thermocline tank instead of a two tank system and
- The integration of the steam generator (SG) that feeds the power block within the storage tank

This new concept has been already tested and verified at prototype scale in Casaccia Research Centre of ENEA (Italy), finding out that the integrated water-steam loop with the storage tank induces a natural convection phenomenon in the molten salt bulk able to hold, after an initial transient period, the integrated water-steam loop operating in quasi-steady state conditions. Thus, with a pressure up to ~40 bar, the sub cooled water comes into the water-steam loop at ~250º C, and exits, as superheated steam, at up to ~500º C.

With the objective of attaining deeper knowledge of the physical phenomena occurring during system operation and therefore, improving future designs at real scale, one of the activities placed in the OPTS project is the analysis and simulation of the prototype already erected in Cassacia. In this way, this paper presents a CFD study that aims reproducing the experimental data of such prototype in a discharge process, starting from a uniform temperature tank (fully charged tank), so its transient thermo hydraulic behaviour can be better understood.

2. Experimental set up

2.1. Prototype and water-steam loop

The prototype erected at Casaccia (Rome) is based on a joint patent between the company Ansaldo Nucleare S.p.A (Italy) and ENEA Research Centre (Italy) [3]. It is a tank with almost 2 m diameter (1.98 m) and around 2.8 m high. It is filled with around 12000 kg of molten solar salt (60% weight $NaNO_3$ + 40% weight KNO_3) and air. It has a vertical steam generator (SG), located at one side of the tank, an electric heater of 100kW, at the opposite side of the SG and some instrumentation (Fig. 1).

The water-steam loop is divided in several sections and has various pieces of equipment, among which it can be highlighted the steam generator, a water pump –by which the water mass flow is controlled, an electric boiler–which preheats the water before entering the SG, avoiding any thermal stress, an air cooler –which condenses the steam exiting the SG, and a regenerator. The SG has three main components from the thermal point of view:

- the downcomer, which places the water at the bottom of the SG without any heat exchange with the molten salts in between,
- three concentric coils of different radius, where the heat transfer between salts and water takes place (active zone) and,
- a blanket, which isolates the molten salts in the SG from the bulk of molten salts.

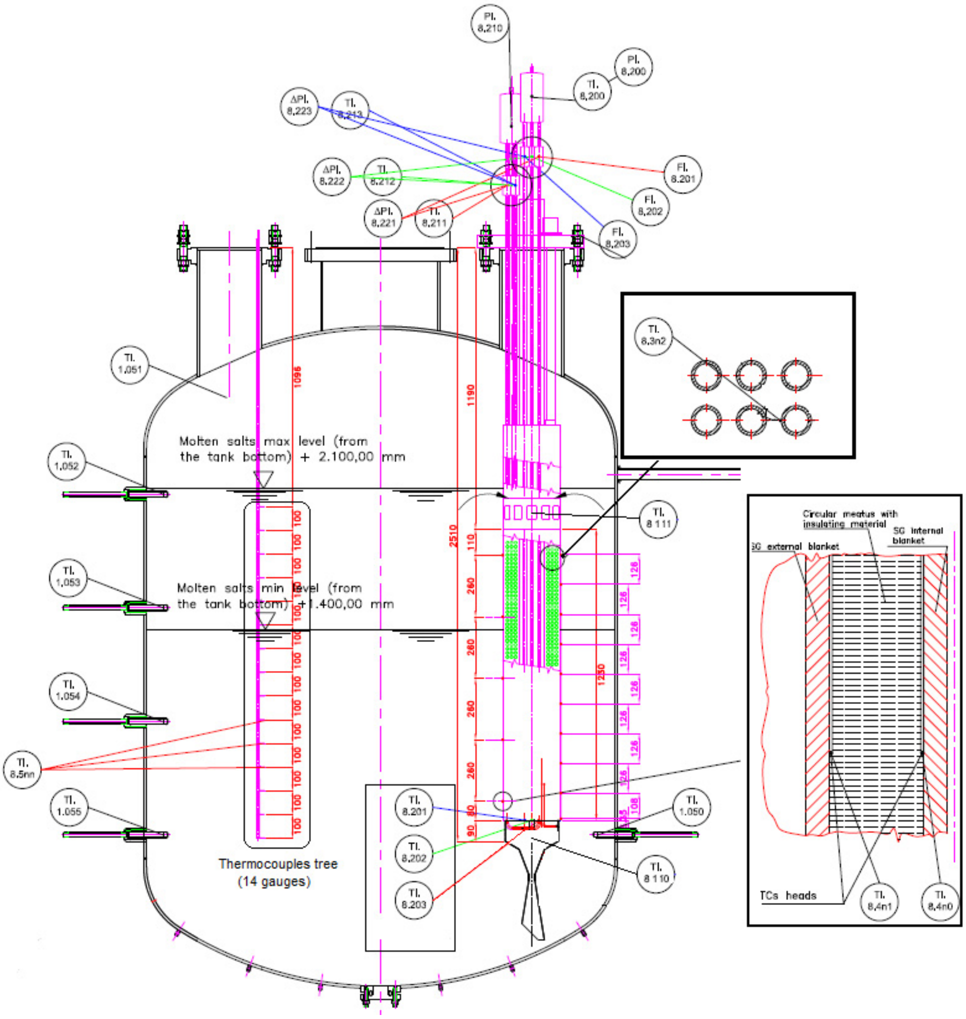

Fig. 1: Photo (top) and scheme (bottom) of the TES-SG prototype in Casaccia (Rome)

2.2. Measuring points

The prototype and the water-steam loop have many different measuring points of different type (Fig. 1): temperature gauges placed in the various media of the prototype (molten salts, water-steam and air), at various positions of metallic components (tank walls, SG-blanket walls, SG-coil walls (inner coil)); pressure gauges at the water-steam loop inlet and outlet, differential pressure gauges between the inlet and outlet of every coil, flow meters at the inlet of the SG, (before the downcomer) and at the inlet of every coil.

The experimental data of the water-steam loop is used mainly for:

- identifying the time range where conditions are more or less stable, and thus defining the test frame where direct experimental data (thermal data of molten salts) can be used for validating the CFD model,
- obtaining indirect experimental data (hydrodynamic data of molten salts) which can be also used for validating the model during all test and,
- defining boundary conditions.

Boundary conditions and some other assumptions are supported by experimental temperature of: the outer wall of the SG coil (inner coil), external wall of the SG blanket and the tank walls.

The direct experimental data of the bulk molten salts are one of the figures to validate the CFD model here presented. With a thermocouples tree with 14 gauges (TI_8_5nn), placed along the electric heater, it is possible to know the temperatures of the bulk molten salts at different heights during the test. All the experimental data are registered and stored every 5 s.

The indirect experimental data, obtained from the energy balance between the molten salts of the tank and the water-steam of the loop, are the other figure to validate the model presented.

The induced molten salt mass flow that moves inside the SG during the test, $\overset{\bullet}{m}_{salts}(t)$, is calculated by means of:

$$\overset{\bullet}{m}_{salts}(t) = \frac{\sum_{coil\_i=1}^{3} \overset{\bullet}{m}_{w.s.}(t)_{coil\_i} \cdot \left(h_{w.s.}(T_{s.out}(t)_{coil\_i}, P_{s.out}(t)_{coil\_i}) - h_{w.s.}(T_{w.in}(t)_{coil\_i}, P_{w.in}(t)_{coil\_i})\right)}{Cp_{salts}(T_{salts.out}(t)) \cdot T_{salts.out}(t) - Cp_{salts}(T_{salts.in}(t)) \cdot T_{salts.in}(t)}$$

Where, $\overset{\bullet}{m}_{w.s.}(t)_{coil\_i}$ is the direct experimental water-steam mass flow in each SG coil (FI_8_201,202,203), $h_{w.s.}$ the flow enthalpy evaluated at $T_{s.out}(t)_{coil\_i}, P_{s.out}(t)_{coil\_i}$ (direct experimental steam temperatures and pressure at the outlet of each SG coil (TI_8_211,212,213 and PI_8_210)) and $T_{w.in}(t)_{coil\_i}, P_{w.in}(t)_{coil\_i}$ (direct experimental water temperatures and pressure at the inlet of each SG coil (TI_8_201,202,203 and PI_8_200)), $T_{salts.out}(t)$, $T_{salts.in}(t)$ the direct experimental molten salts temperatures at the lower and upper parts of SG (TI_8_110, 111) and Cp_{salts} the molten salts heat capacity evaluated at $T_{salts.out}(t)$, $T_{salts.in}(t)$. All these experimental data are also registered and stored every 5 s.

2.3. Reference test

The experimental data used to validate the CFD model here presented correspond to a test day in which the charge of the storage was performed by heating the molten salts with the electric heater until they were at an homogeneous temperature of 483.4º C (time range between 0 and 0.5 h, Fig. 2).

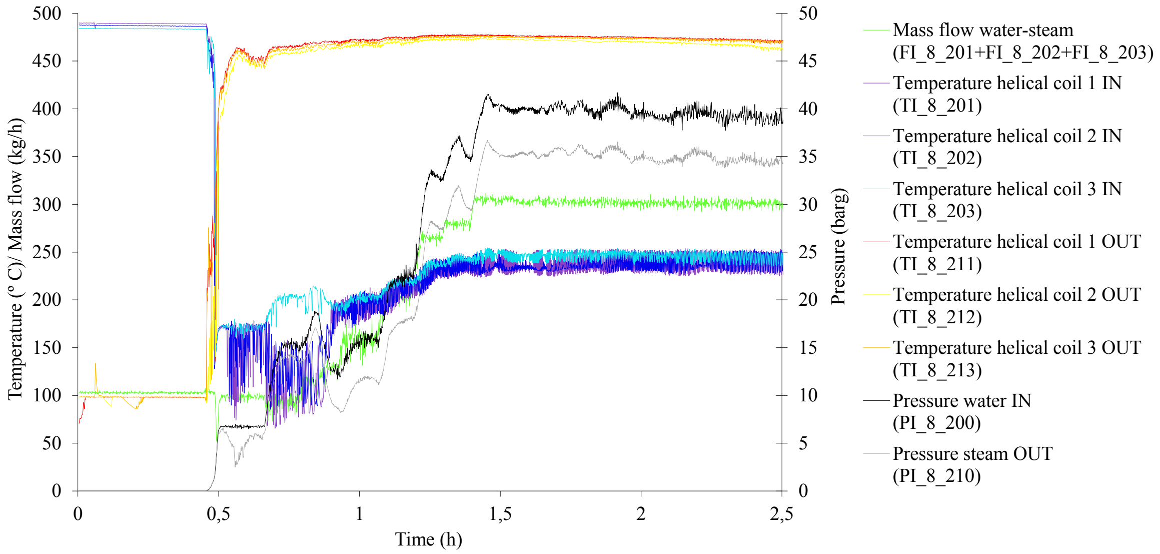

Fig. 2: Experimental data water-steam loop during discharge

At 0.5 h and after switching off the electric heater, the saturated water starts circulating through the SG, i.e., discharge process begins. After a transient period of 1 h, temperatures and pressures of the water-steam loop remain quasi-constant until 2.5 h (moment from which starts the end of the test). This is not the case for the bulk molten salts that, during this period (from 1.5 h to 2.5 h), moves due to natural convection induced by the heat transfer to the SG.
The tank becomes a thermocline tank. The molten salts bulk movement can be seen in the change of bulk temperature stratification with time (Fig. 3).

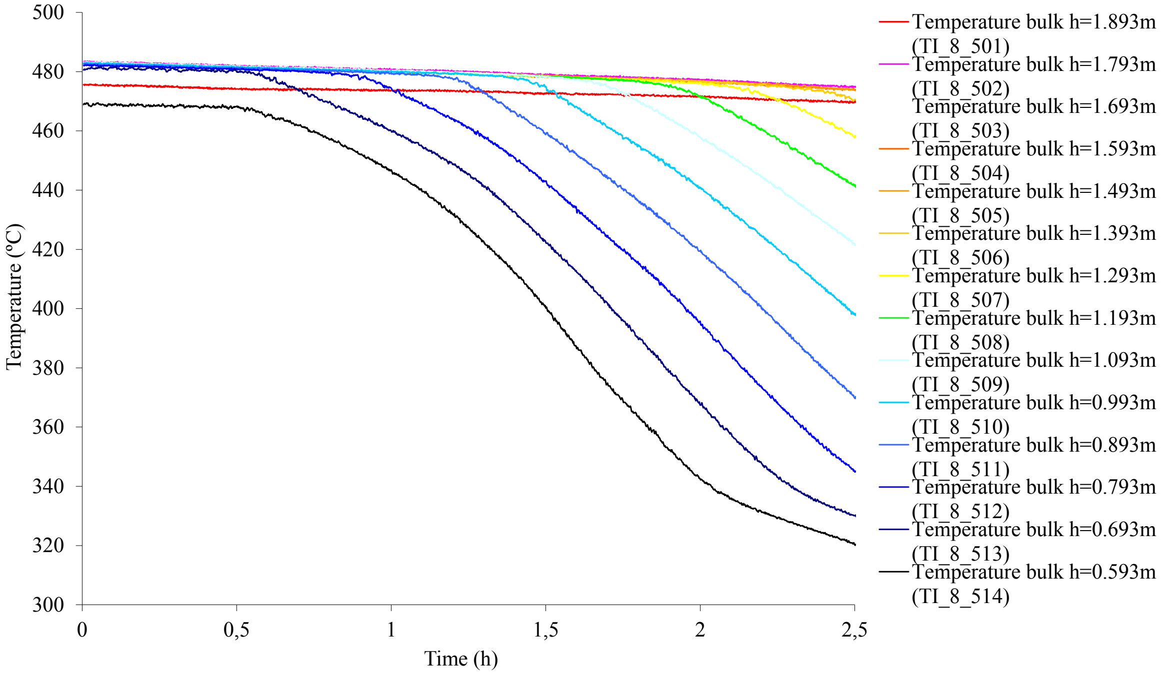

Fig. 3: Temperatures of the molten salts bulk during discharge (14 gauges (TI_8_5nn))

3. CFD model

The CFD model here presented intends to reproduce mainly the transient thermo hydraulic behaviour of the bulk molten salts while water-steam conditions remain stable in discharge. Thus the electrical resistance is not included in the model.

3.1. Geometrical model

For simplicity and computer time consuming, a 2D axisymmetric model is proposed and only half of the SG is considered (Fig. 4).

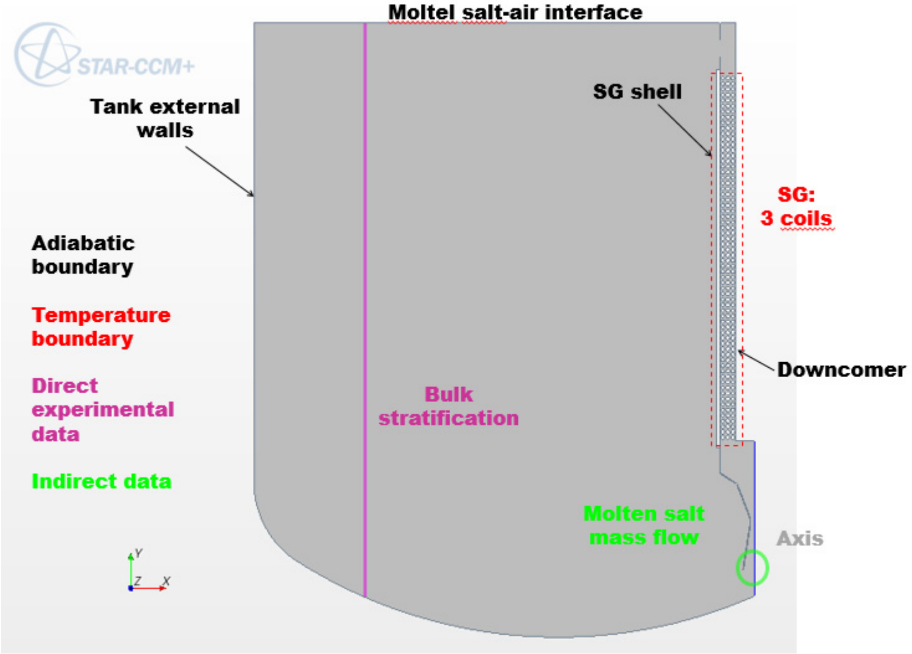

Fig. 4: Geometric model, identification of boundary conditions (adiabatic/temperature boundaries) and locations of experimental data used as reference (direct/indirect data)

3.2. Meshing and physical model

The domain has been discretized with a polyhedral mesh of STAR-CCM+, which is the CFD commercial software used for this study. The maximum cell size is fixed in $5 \cdot 10^{-3}$ m. This size and a time step of 10 s ensure a good convergence of the numerical model without an excessive computer time consume. The residues keep in the 10^{-3} and 10^{-4} range.

From the numerical time point of view has been necessary to use an implicit unsteady model. A segregated formulation has been considered for both the flow and the energy. The linkage between the momentum and continuity equations is achieved with a predictor-corrector approach. The complete formulation can be described as using a collocating variable arrangement and a Rhie and Chow pressure-velocity coupling combined with a SIMPLE type algorithm.

Besides, the following approaches have been considered:

- a RANS model for the viscous regime. Closing the RANS model equations is made with the Realizable K-E Two-Layer model [7], having the flexibility of an all y+ wall treatment,
- Boussinesq model, where the variation of density with temperature is only considered in the buoyancy forces. In other terms the density is considered constant and,
- thermo physical properties of molten salts heat capacity, thermal conductivity, dynamic viscosity and thermal expansion coefficient depend on temperature [8].

3.3. Boundary and initial conditions

For a time lower than 0.5 h, the molten salts and the SG three coil walls temperatures are assumed to be 483.4º C. Any boundary surface or interface is assumed to be adiabatic (Fig 4). This latest condition seems to be a good approximation, not only because there is a 0.4 m insulating layer externally to the tank and the SG insulating blanket is 0.014 m thick, but also because looking at the temperatures at these surfaces the stratification keeps being the same as in the bulk region (Fig. 5 and 6).

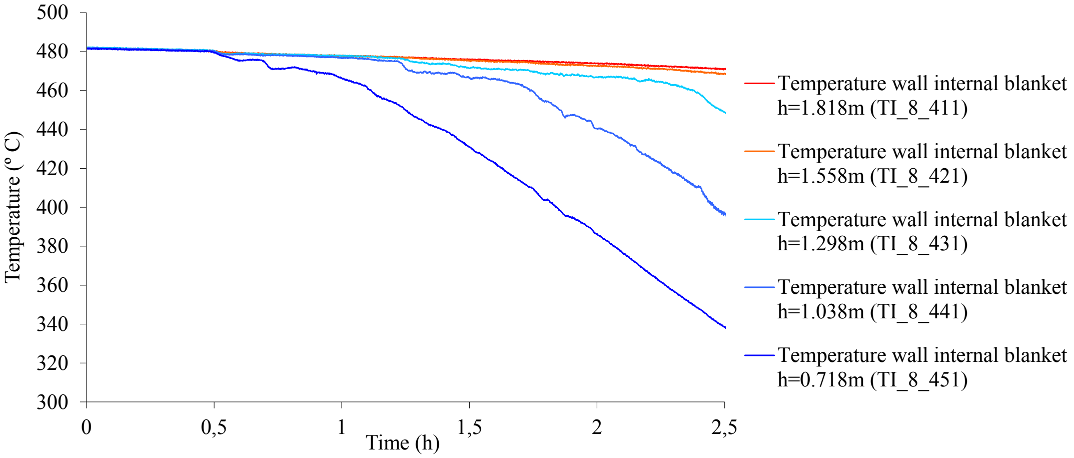

Fig. 5: Temperatures of the outer wall of the internal blanket during discharge

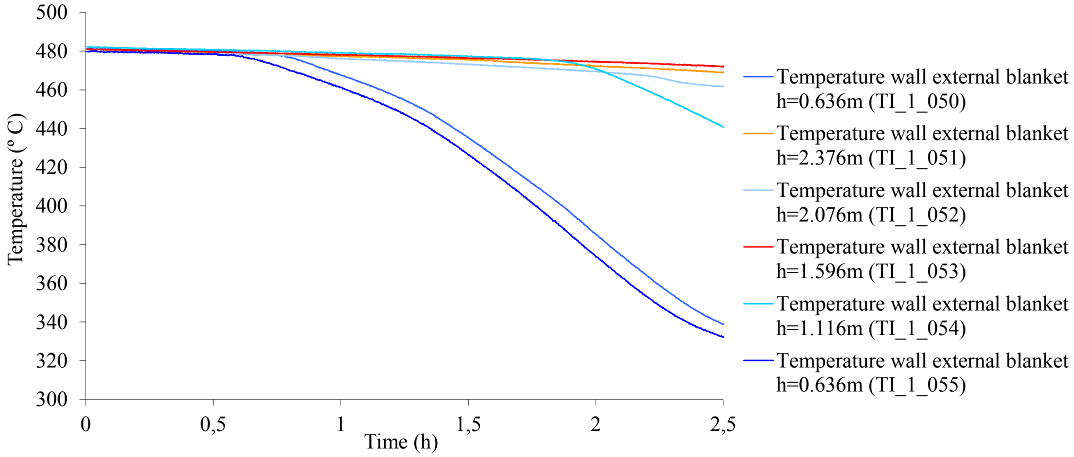

Fig. 6: Temperatures of the wall of the external blanket during discharge

It was found that the level of the molten salts was lower than expected (2.1 m from the bottom) since the temperature gauge apparently placed just below this level registered similar values as the gauge above that level (in the air cavity closing the tank). An estimated height of 2 m was chosen as molten salt level.

For a time above 0.5 h, the temperature profile of the SG three coil walls (T_{SG}) are those experimentally measured for the inner coil in its external surface at t=2.5 h (Fig. 7). Although there are only experimental data of one of the three coils, the heat transfer coefficients between the steam and the walls are assumed to be good enough for having the same temperature profile in all the three coils.

$$T_{SG} = \left\{ \begin{array}{ll} If\ t \leq 0.5\ h & 483.4℃ \\ If\ t > 0.5\ h & T(Height) \end{array} \right\}$$

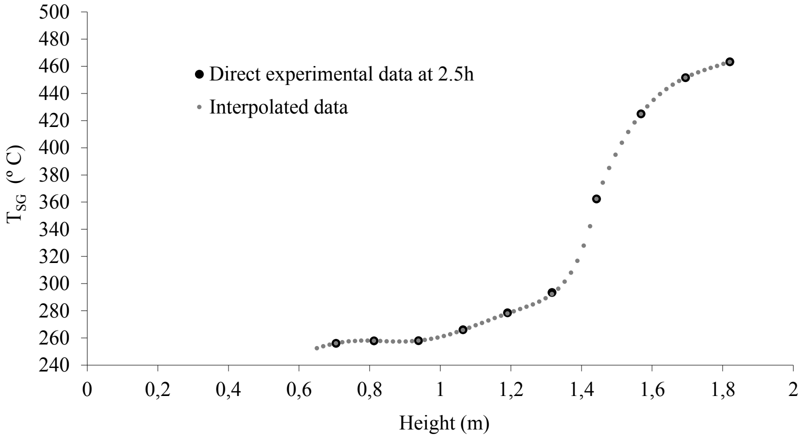

Fig. 7: Temperature profile of the SG three coil walls

It is important to note that the boundary conditions are assumed from 0.5 h on, is independent of time.

4. Results

4.1. Thermal results of molten salts

In Fig. 8 numerical and experimental data are compared for the time range where the water-steam loop is under stable conditions: from 1.5 h to 2.5 h. The direct experimental results correspond to the temperature gauges in the thermocouple tree every half of an hour (1.5 h, 2 h, and 2.5 h).

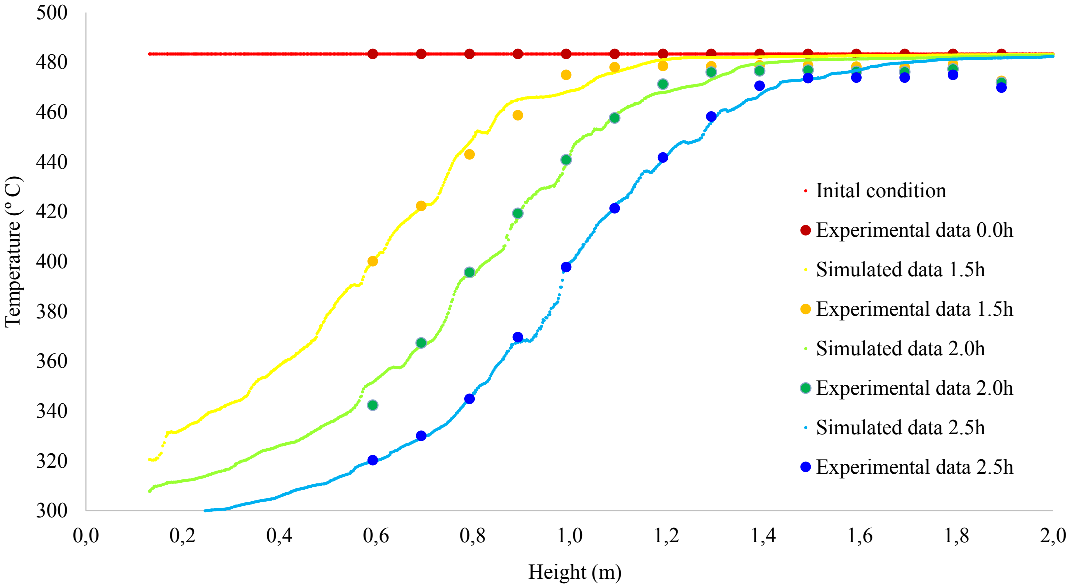

Fig. 8: Bulk stratification during discharge

4.2. Dynamic results of molten salts

In Fig. 9 numerical and experimental data are compared during all test: from 0.0 h to 2.5 h. The indirect experimental results correspond to the data obtained from the energy balance between the molten salts of the tank and the water-steam of the loop every 5 s.

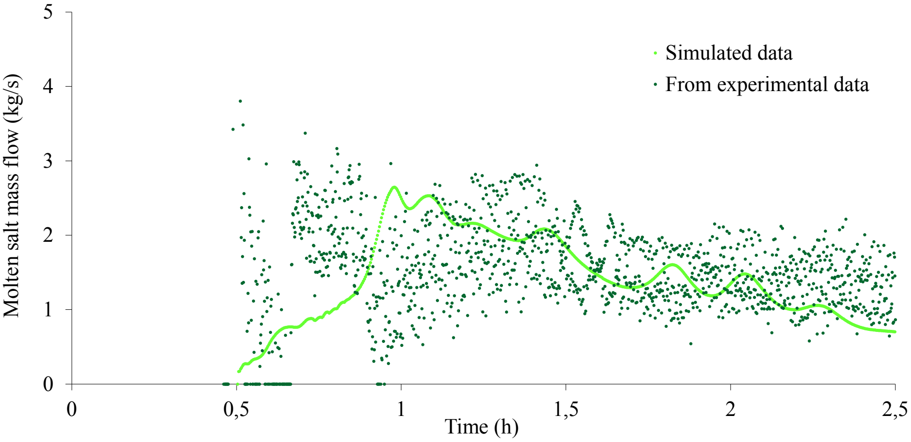

Fig. 9: Induced molten salts mass flow during discharge

The good agreement between numerical and experimental values (direct and indirect) is evident from this figures. Thus a 2D axisymmetric transient model with boundary conditions constant with time is able to reproduce very well the advance of the stratification temperature profile of the bulk molten salt during a discharging process with an integrated SG, as well as, the evolution of the associated induced molten salt mass flow that moves inside the SG.

The velocity of thermocline region remains nearly constant as can be seen.

The CFD techniques, together with a methodology similar to that used in this study, are shown as a good starting point for the analysis of other related phenomenologists, present in this innovative storage system.

This would achieve the goals of certain OPTS project tasks.

Acknowledgements

The authors would like to acknowledge the E. U. through the 7th Framework Programme for the financial support of this work under the O.P.T.S. project with contract number: 283138.

References

[1] Libby, C. Solar Thermocline Storage Systems: Preliminary Design Study. Final Report, June 2010. EPRI, Palo Alto, CA.
[2] Querol, P. et al. Single Tank Thermal Storage Prototype. Proceedings of SolarPACES 2012.
[3] Flueckiger S.M., Yang Z. and Garimella V. Design of Molten-Salt Thermocline for Solar Thermal Energy Storage. CTRC Research Publications (191) (2013).
[4] International application published under the patent cooperation treaty (PCT). International Publication Number WO 2012/080970 A2.
[5] STAR-CCM+ Version 7.06.012 Tutorial Guide, CD-adapco Support.
[6] Ahmed M H. Unsteady Numerical Simulation for Studying the Thermocline Phenomenon inside a Storage Tank for Molten Salt. Journal of Applied Sciences Research 8(8) (2012) 4635-4644.
[7] Versteeg H.K. and Malalasekera W. *An Introduction to Computational Fluid Dynamics, the Finite Volume Method.* Prentice Hall; 2007.
[8] Bradshaw R.W. and Carling R.W. A Review of the Chemical and Physical Properties of Molten Alkali Nitrate Salts and Their Effect on Materials Used for Solar Central Receivers, SAND87-8005, April 1987.