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Proposal of a thermocline Molten Salt Storage Tank for District Heating and Cooling

A. Abánades[1,*], J. Rodríguez-Martín[1], J.J. Roncal[1], A. Caraballo[2], F. Galindo[2]

[1]Universidad Politécnica de Madrid; ETSII, c/José Gutiérrez Abascal, 2; 28006-Madrid

[2]FERTIBERIA; Paseo de la Castellana, 259D; 28046-Madrid

[*]Corresponding author: alberto.abanades@upm.es

Abstract

Energy storage is one of the critical components in thermal district heating and cooling (DHC) facilities with a high share of renewable energy supply, mainly if provided by intermittent energy sources as solar. Currently, DHC energy storage is based on water tanks, which operational temperature range is suitable for domestic hot water and cooling based on simple absorption chillers. Moreover, water storage cannot be linked to medium temperature processes as double effect absorption chillers or other services requiring temperatures above 100 ºC. Molten salts are widely used for heat storage in concentrated solar plants (CSP) operating with temperatures above 250 ºC, limited by the melting/solidification of available commercial solar salts.

Fertiberia is developing innovative molten salt mixtures lowering such melting temperature below 150ºC. The availability of a storage medium in a temperature range up to 250 ºC might increase the solar share in DHC installations, integrating concentrated solar technologies and reducing the dependency for natural gas or combustion boilers. In this communication, a molten salt storage tank operating in thermocline mode will be proposed in the framework of the WEDISTRICT project. The project seeks to deliver the highest possible share of renewable sources for the energy needs of a district demand.

Keywords: Molten salts, District Heating, Thermocline tank, DHC

1. Introduction/Background

Residential energy demand constitutes a significant part of the energy consumption in the European Union. Energy decarbonization in Europe requires the implementation of low-Carbon technologies in district heating and cooling facilities. From this perspective, the WEDISTRICT project seeks to deliver the highest possible share of decarbonized energy for a district heating demand, integrating a variety of thermal renewable technologies (as biomass, geothermal and solar), energy harvesting and recovery technologies, and thermal cooling systems, as the RACU (Renewable Air Cooling Unit, based on desiccant evaporative wheel) or advanced absorption chillers. In this context, energy storage is called to play a pivotal role for a suitable matching between energy generation and demand.

The integration of efficient thermal cooling technologies based on advanced absorption chillers, and optionally, some other services, into a heating and cooling network, requires the posibility of delivering energy at temperatures above 100 ºC (the physical limitation of water storage). Therefore, only manageable energy sources as fossil (natural gas, or coal), and biomass are implemented up to this day to fulfil the needs, for instance, of double effect absorption chillers with COP (Coefficient of Performance) larger than unity. The integration of intermittent thermal energy sources, as solar, for their fully contribution to medium temperature application needs the development of storage options based on fluids with a stable performance at this temperature range, namely between 130 and 300 ºC.

Thermal energy storage for concentrated solar power is commercially available by molten salt accumulation in two isothermal tanks[1], and tested by thermocline tanks [2]. The operation of concentrated solar power plants (CSP) is intended at higher temperature as technically feasible to provide the highest achievable plant efficiency. Nitrate salts [3] are the commercial standard as Heat Transfer Fluid (HTF) for CSP, with operational ranges roughly between 250 and 600 ºC due to its melting point (above 200 ºC) and their degradation rate at high temperatures. Carbonates [4] have been proposed as well to increase the upper temperature operation. Unfortunately, none of those alternatives already developed or under development are suitable for district heating and cooling applications. Another alternative is the utilization of phase-chase materials (PCM)[5,6], but their application is not compatible with the usual temperature change on the service and return water flows of a district heating depending on the season.

The application of molten salt storage to a district heating and cooling installation requires the development of new salt mixtures that could overcome the solidification risk of state-of-the-art solar salts. We estimate that the application window for molten salts in DHC is open if their solidification could be well below 150 ºC. This is the main challenge of the application of molten salt storage tanks to the residential sector, and the main innovation regarding storage technology into the WEDISTRICT project.

The molten salt tank in the WEDISTRICT project is originally intended to be installed in the Alcalá demo-site, where a heating and cooling network will be tested to cover the demand of the building hosting the CEPSA R&D center. The DHC network will integrate a low-emission biomass boiler, several types of solar technologies (Fresnel and parabolic troughs, and a low concentration flat plate collector), and different technologies to provide the heating and cooling demand. The molten salt tank, operating between 150 and 235 ºC, will be connected to the concentrated solar collectors in parallel with the biomass boiler that will act as back up for the facility.

In this paper, the description of the characteristics of the molten salt mixtures able to operate at 150 ºC under development by FERTIBERIA is the main content of the next section. The technological gap is significant, as the temperature required in district heating is much lower than in solar thermal plants. Solidification risks are one of the main limiting aspects of the current molten salt loops in power installations, either as storage media, or as heat transfer fluid.

Further sections will describe the proposal in the framework of the WEDISTRICT project of a thermocline tank for the verification of the operation of those new salts in an environment far from its previous application, namely, solar thermal power plants. There has been previous works in the field of modelling [7–9] and experimental analysis of this kind of tanks, either filled with water in domestic application [10] or molten salts for CSP, with a special emphasis on the analysis of the stratification [11] and temperature position of the thermocline layer. Based on that experience, the conceptual design of the tank to be commissioned in WEDISTRICT has been done.

2. Molten salt preparation for district heating and cooling operation range

The composition of ternary salts based on Strontium, Sodium and Potassium nitrates (Sr (NO3)2, NaNO3, KNO3) has been screened, searching from combinations and eutectic compositions that could provide a low melting point molten salt. Additionally, quaternary mixtures adding Calcium nitrates (Ca (NO3)2) and Sodium nitrides (NaNO2) have been tested. A first literature review was done to analyze the commercial suitable candidates and a thermodynamic modelling using CALPHAD methodology [12], that is an established methodology to evaluate thermal-physical properties for combination of materials and salts [13,14]. From the evaluation of a set of combination of nitrate salts, ternary diagrams, as the example shown in Figure 1 are produced.

As a result of the work carried out with the combination of alkali and alkaline earth nitrates and nitrites, a quaternary salt was produced for its utilization in WEDISTRICT storage tank in Alcalá, denoted as FERT-1. The thermal-physical properties of that salt have been determined: density, viscosity, specific heat capacity, and thermal conductivity, and compared with the Solar Salt (state-of-the-art TES material), shown in Figure 2.

Corrosion behaviour of the TES material was one of the main concerns for the design of the system. Conventional stainless steels have been tested 2000 hours with FERT-1 salt at 425 °C. Rectangular, tube, weld and under stress probes were tested in order to determine general, intergranular, weld and under stress corrosion. The results show corrosion rates below 0.1 mm/y for every stainless steel, including AISI 430.

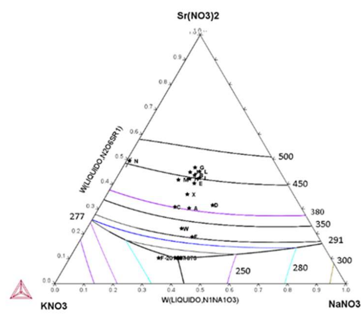

Figure 1. Example of ternary diagram modelled for Sr/K/Na nitrates.

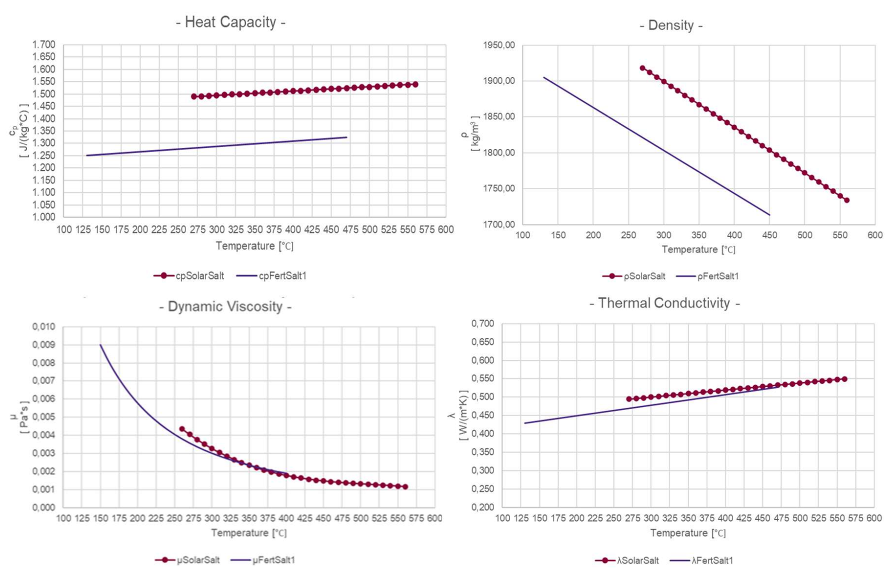

Figure 2. Thermal-physical properties of the FERT-1 mixture and the Solar Salt.

As a reference for the material selection of the tank, we can see at the work of Fernández et al. [15] a rigorous corrosion analysis for nitrate-based salts. The corrosion results for AISI 304 as reference austenitic steel, and AISI 430 as ferritic steel is presented in Figure 3. It can be noticed that corrosion drops drastically with temperature, being the expected WEDISTRICT operation well below 390 ºC, which would allow the safe utilization of austenitic or ferritic steels.

The low temperature operation gives the possibility of using carbon steels as 516 Gr 70, that are affected by a high corrosion rate at T > 400 ºC, and that could offer lower costs and better delivery and manufacturing in more competitive time frames. To increase structural safety respect to corrosion it is proposed a corrosion allowance of 3.2 mm.

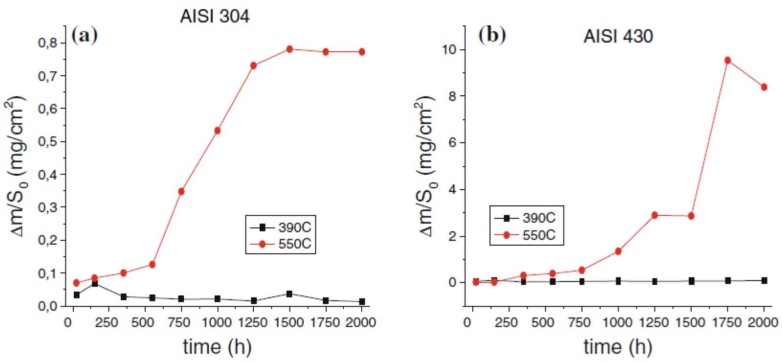

Figure 3. Corrosion test on AISI 304 and AISI 430 steel

Another important issue is the stability of the eutectic mixture. Two kinds of reactions can occur at high temperatures for nitrate mixtures. In the case of alkaline nitrates, it decomposes into the nitrite. Nitrites are highly soluble in nitrates and their presence leads to a decrease in the freezing point of the mixture. Nitrites can decompose into alkaline oxides, nitrogen and nitrates again. This mixture can rapidly react to produce alkaline hydroxides (very corrosive) and carbonates. These species present a limited solubility in molten nitrates, so they can precipitate leading to problems with valves and pipelines. In the case of the WEDISTRICT project, temperatures are expected well below 250 ºC, being under the threshold to activate this second transformation for alkaline nitrates. The decomposition of salt nitrates into nitrogen and nitrogen oxide is a risk that has been tested for the quaternary salt mixture developed by Fertiberia. As a conclusion, for the quaternary eutectic salt FERT-1, a temperature range of 110-500 ºC is safe regarding stability criteria.

Comentado [A1]: Podría ser "eutectic point"/"eutectic mixture"/"eutectic salt"

3. Analytical analysis of the thermocline tank

The storage tank that is proposed has as starting point, and most important parameter, the storage capacity that will be needed in the real application, the Alcalá demo-site. From the storage capacity point of view, the rest of the conceptual and physical design of the tank will be elaborated based on 1-D model, as well as dynamic model to estimate the response of the tank. From the available information, a proposed design for the storage tank will be delivered for its detailed engineering and commissioning.

3.1 Storage capacity

The storage capacity of the tank has been evaluated from the analysis of the annual production of the solar field of the Alcalá site in WEDISTRICT, and according with the following criteria:

- The storage is sized for the accumulation of available energy in a daily basis, following load cycles when solar irradiation might be available, and discharge during the rest of the time. The maximum expected daily energy production is 4.5 MWh/day. The total nominal power of the concentrated collectors is of 411,35 kW.

- Scale for demonstration purposes: The storage capacity in molten salts should be done at a scale suitable to demonstrate the utilization and performance of the technology in a real district heating and cooling environment. Storage capacities of the order of MWh should be enough to achieve operational experience in production environments

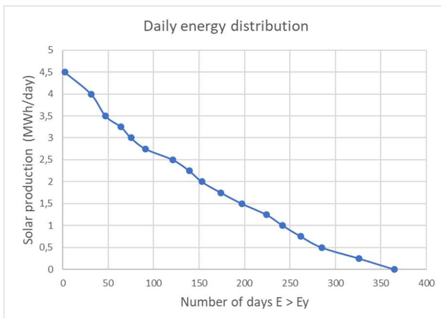

Figure 4. Daily energy generation distribution in Alcalá site.

Figure 4 shows the accumulative distribution of daily solar production along the year. This information shows that there are more than 215 days in the year producing less than 2 MWh. Following this criteria, the storage capacity of the molten salt tank has been set to 2 MWh, to operate with solar production availability, keeping the storage volume into the budget restrictions and complying with the practical increase in TRL, testing the performance of a storage system into a relevant practical environment.

3.1 Static model for nominal design

The design of a thermocline tank filled with molten salt is based on a cylindrical steel tank with distributors at the inlet and outlet of the salt, and a vast central region filled with a packed bed. The packed bed has a very important impact on the stability of the thermal profile of the tank and its capacity, as described by the other authors [8]. An Engineering Equation Solver model has been developed to evaluate the basic parameters of the thermocline tank vessel, including the mass and energy flow balances.

The tank is modelled by an effective storage volume, where the thermocline layer should be located at any time, some space for fluid buffering, and two auxiliary tanks that absorbs fluctuation of the molten salt flow at charge/discharge. In those auxiliary tanks, the molten salt pumps are immersed. The main tank is filled with quartzite rocks [16]. The thermal capacity of the effective storage volume is estimated by the aggregation of the molten salt and rock-bed capacities as:

$$\overline{\rho \cdot C_{p_{eff}}} = (\rho \cdot C_p)_{salt} \cdot \varepsilon + (\rho \cdot C_p)_{rock} \cdot (1-\varepsilon) \qquad \text{(Eq. 1)}$$

Being ε, the porosity of the rock, the total energy accumulated in the effective storage module is estimated as:

$$\mathrm{E} = \overline{\rho \cdot C_{p_{eff}}} \cdot \mathrm{V_{eff,st}} \cdot \Delta\mathrm{T} \qquad \text{(Eq. 2)}$$

The total volume of the tank is evaluated as the effective storage tank plus the volume that is assigned for upper and lower buffering, including the vessel head. From the rest of the storage requirement, as the exchange power, the mass flow rate of the molten salt to enter the tank is estimated. The dimensions of the tank, and the characteristics of the porous filling will serve to check the stability criteria of the thermocline layer, and the pressure loses due to the molten salt displacement inside the tank. In particular, the stability criteria is established[11] by the evaluation of a critical velocity.

$$u_c = gK\frac{(\rho_1-\rho_2)}{(\mu_1-\mu_2)} \qquad \text{(Eq. 3)}$$

With g as the gravity, the density and viscosity differences and the conductivity K. For the FERT-1 salt, both the viscosity and the density are decreasing versus the temperature, being u_c positive. If the velocity of the salt into the tank is lower that the terminal velocity, the thermocline layer is stable during charge and discharge. For the tank operation, with a power exchange of 411 kW, it has been checked that velocities in the smaller tanks are well below 7.65 mm/s, that is the critical velocity.

The pressure losses in the tank are evaluated with the Ergun equation, applicable to porous media.

$$\frac{\Delta P}{H_{sto}} = \frac{150\cdot\mu}{d_p^2}\cdot\frac{(1-\varepsilon)^2}{\epsilon^3}\cdot u_f + \frac{1{,}75\cdot\rho}{d_p}\cdot\frac{(1-\varepsilon)}{\epsilon^3}\cdot {u_f}^2 \qquad \text{(Eq. 4)}$$

The particle diameter of the rocks in the bed is a parameter that depends on the size of the rock stones and its physical meaning is similar to a dimension characteristic length. The pressure losses may change slightly with the variation of the average thermal-physical properties of the salt in the porous media versus temperature.

The static model has been implemented in Engineering Equation Solver (EES) to evaluate the nominal design parameters. Figure 5 shows a screenshot of the diagram window of the EES model. The nominal design of the storage tank is summarized in Table 1.

3.1 Dynamic model

The numerical analysis solves a 1-D model in accordance with the basic scheme depicted in Figure 6. The model describes an inlet mass flowrate, either hot at the top or cold at the bottom, and an outlet molten salt flow rate. The tank is assumed to be a vertical cylinder filled by a porous media. The cylinder is divided in N segments. The molten salts flow through those segments that are considered as nodes for the resolution of the balance equations. Each cylindrical node is defined by the tank diameter (D) and node height (Δx), and characterized by a homogenization of the thermal-physical properties and its temperature.

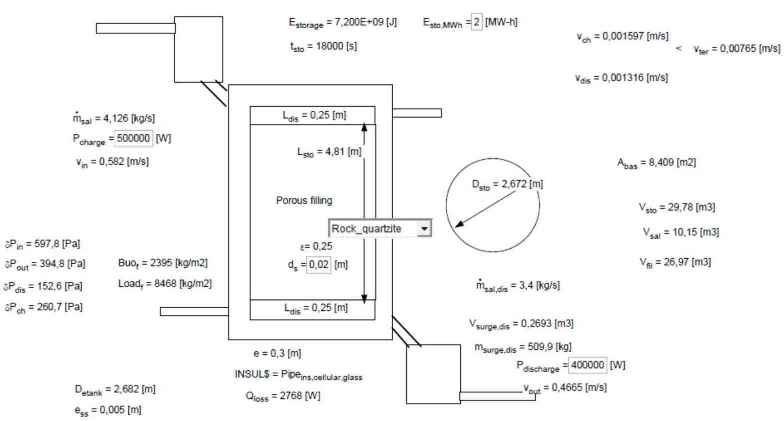

Figure 5. Diagram window developed into EES software package

Table 1. Nominal specification for the molten salt storage tank

Specification	Value	Unit
Storage capacity	2	MWh
Exchange power	411.3	kW
Max. temperature	235	ºC
Min. Temperature	150	ºC
Rock type	quartzite	
Tank volume	33.58	m^3
Effective volume	30.53	m^3
Tank inner diameter (D_{sto})	2.785	m
Tank height (H)	5.513	m
Active height (H_{sto})	5.013	m
Bed porosity (ε)	0.25	-
Molten salt in tank	10.68	m^3
Rock volume	22.9	m^3

The model solves the energy balance of each node. Taking into account that each node is composed of a solid material and the molten fluid, the energy balance at each node is defined by the following equations:

In the molten fluid:

$$\varepsilon\left(\rho c_p\right)_f \frac{\partial T_f}{\partial t} + \varepsilon u\left(\rho c_p\right)_f \frac{\partial T_f}{\partial x} = k_{eff}\frac{\partial^2 T_f}{\partial x^2} + h_{sf}A_{s,f}\left(T_s - T_f\right) + U_w a_w\left(T_{env} - T_f\right) \quad \text{(Eq. 5)}$$

In the solid material:

$$(1-\varepsilon)\rho_s c_{p,s}\frac{\partial T_s}{\partial t} = h_{sf}A_{s,f}\left(T_f - T_s\right) \quad \text{(Eq. 6)}$$

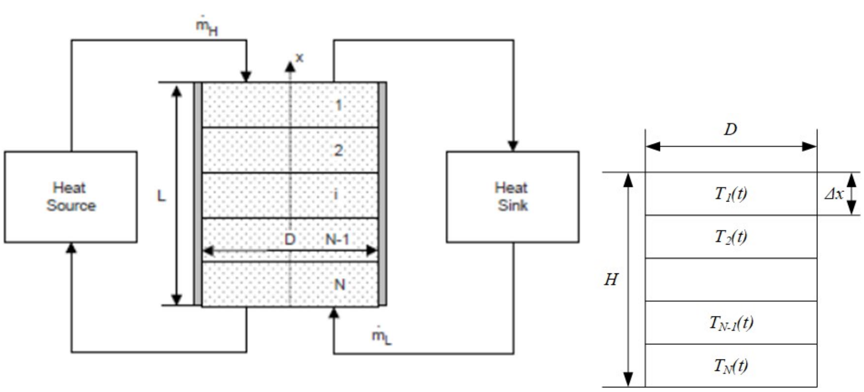

Figure 6. Scheme of the dynamic model of the tank

The model has been qualified with available data in literature of a water thermocline tank [9] and the proposal for thermal storage in the SolarOne plant for a storage capacity of 170 MWh, with the Caloria HT-43 thermal oil, into a tank with rock and sand as porous filling material [17]. The results of those qualifications are shown in Figure 7. The application of the dynamic model to the nominal design described in Table 1 in Figure 8, normalized into the effective volume.

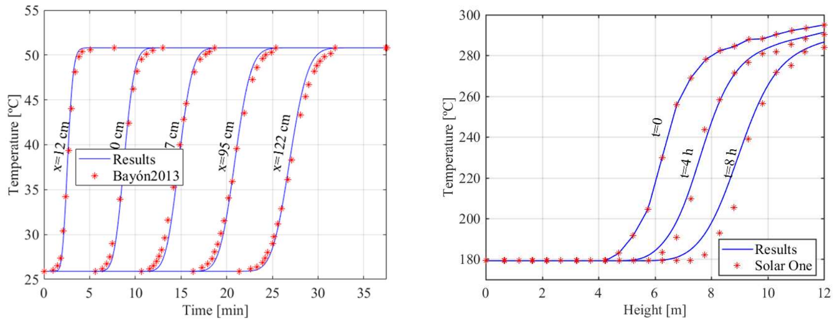

Figure 7. Qualification of the dynamic model.

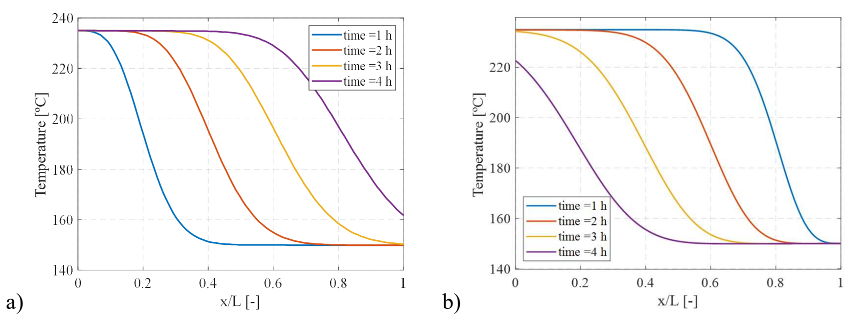

Figure 8. Results of the charge (a) and discharge (b) thermocline evolution in the WEDISTRICT storage.

4. Conclusions

In this paper, it is shown the work for the proposal of a medium temperature storage for district heating and cooling. The availability of stored heat above 150 ºC increases the possibility of applying concentrated solar technologies, in particular, to fulfil demand linked to advanced absorption chillers, or even more demanding, from a temperature point of view, thermal services. This could be an important contribution for the decarbonization of the energy consumption in the residential sector.

Energy storage for district cooling is now performed under the limitation of the liquid phase range of water, restricting cooling to single-stage absorption chillers. The utilization of molten salts enables the increase in temperature availability. They are commercially used for thermal storage in solar thermal plants, traditionally seeking high operational temperatures to increase plant efficiency. Nevertheless, commercially available nitrate salts have a safe liquid range that is not suitable for district applications. In the framework of the WEDISTRICT project, new nitrate salt mixtures are under development with the main aim to operate below 150 ºC, making feasible the implementation of thermal storage well above 100 ºC for district heating and cooling. Based on that new salt, called FERT-1, a thermocline storage tank is designed and proposed for the commissioning in the Alcalá demo of the WEDISTRICT project. The molten salt tank, operating between 150 and 235 ºC, will be connected to different technologies of concentrating solarcollectors in parallel with the biomass boiler, which will act as back up for the facility. The total volume for a capacity of 2 MWh, corresponding to 4.82 h of the solar nominal concentrated energy production is 30,53 m3, with 20,76 m3 of quartzite rock.

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