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Experimental Test of Characterization of an Innovative Thermal Energy Storage System Based on Low Melting Molten Salt Thermocline Tank Integrated with an Oil Exchanger

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Abstract. Scope of the ORC-PLUS Project is the extension of a solar thermal power plant, already realized in Morocco, by using Fresnel linear collectors technology as a solar field and an ORC system as a heat engine. Besides the additional collector loops, a 20 MWh Thermal Energy Storage (TES) system has been added to the plant for increasing the full load hours and allowing the electricity production in the evening when there are demand peaks. In the case under exam, two different thermal storage technologies have been considered. The first technological option consists of the possibility to utilize a storage system with two internal heat exchangers to charge and discharge the thermal storage system and a low melting ternary salt mixture to exploit the energy of its sensible heat. Since in the solar collectors a mineral oil is used as Heat Transfer Fluid (HTF), the second technological option aims to realize a thermal storage system where the HTF can also be used as Heat Storage Medium (HSM). This solution can be affordable because the oil vapor pressure is lower than the ambient pressure, and mineral oil is much cheaper than synthetic oils. In this second case, to further reduce the cost and to increase the density of the stored energy, a cheap solid filler material has been inserted in the storage tank to reduce the required amount of thermal oil. In the framework of the ORC-PLUS Project activities, three different TES prototypes have been designed and assembled (by CIC, ENEA and F-ISE), in a scale of 1/100 (200 kWh) respect to the pre-industrial TES system that is being to realize at Benguerir (Morocco). The main goal of the TES prototypes was to validate the feasibility of the proposed TES technologies concepts. In this paper, the preliminary results of the testing activities performed by ENEA on his TES prototypes, based on low melting molten salt thermocline, are presented.

INTRODUCTION

The experience gained in the CSP sector in this last years has suggested that a possible field of application of the small/medium CSP power plants coupled with new advanced solutions of TES system could be that related at their employment in the sector of distributed power generation with a strong penetration of the renewable energies. In this application, the Thermal Energy Storage (TES) system is the key component to significantly stabilize local energy generation and increase its annual production in CSP plants. For this application, the possibility to employ the Organic Ranking Cycle (ORC) systems to produce electrical energy is gaining more and more importance in recent years, mainly for small size plants [1-2], because the ORC power unit is characterized by high viability and the possibility to implement the system of remote control. In this frame, thanks to the ORC-PLUS project [3-4] ENEA has developed and tested an innovative TES system. It is based on a low melting molten salt (MS) thermocline. Two integrated oil exchangers permit easy integration with a small CSP plant equipped with a Fresnel solar field and an ORC power unit. They employ mineral oil, at low environmental impact, as Heat Transfer Fluid (HTF).

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TES PROTOTYPE CONCEPT

The TES prototype makes use of the thermocline technology which uses low melting point salt as heat storage medium by exploiting the natural stratification of the molten salts with temperature. It is an indirect TES system where the storage medium is stored inside a tank, and the HTF (a mineral oil) flows into two flat coil Heat exchangers (HXs) allocated inside a special shell that crosses the thermocline layer in a vertical direction (see Fig. 1a). In the top and the bottom of the shell the two HXs are allocated. The upper HX is used during the discharge operation of the TES to allow the HTF warming. The second HX is positioned in the bottom of the shell and is used during the charging operation of the TES to heat the molten salt with the energy provided by an external source.

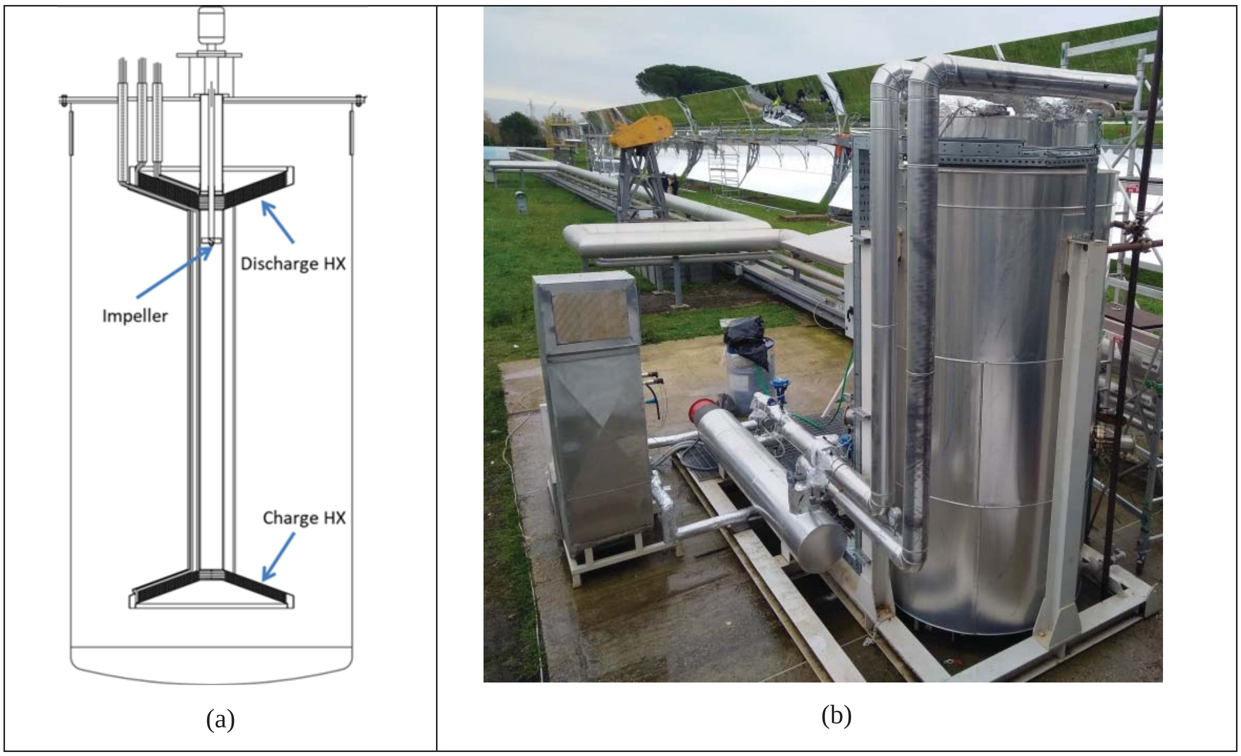

FIGURE 1. Scheme (a) and picture (b) of the coupling CSP-TES-ORC.

This pilot plant mainly consists of the following equipments (Figure 2):

- tank to enclose the molten salt and makes possible the thermal energy storage;
- 2 electrical heaters within the tank to make up the heat losses during no working times as well as to achieve the desired temperature levels before the beginning of the test;
- 1 pump for the oil handling;
- 1 electrical heater to warm the oil in charge mode, simulating the Concentrating Solar power (CSP) effect;
- 1 air cooler to cool the oil down in discharge mode, simulating the Organic Rankine Cycle (ORC) system;
- 1 expansion vessel to manage the oil volume variation with the temperature;
- 2 three-way valves to set up the charge or discharge mode;
- some vent valves to release the air inside the oil circuit if any, and prevent excessive pressure;
- 1 safety valve to avoid risk due to too much pressure;
- piping to join the abovementioned equipment.

In the real plant, the mineral oil in the discharge HX supplies the ORC system, while the external solar plant warms the oil in the charge HX. In charge mode, the temperature difference between the molten salt at the HX outlet and the tank causes the onset of convective motions of the salt that, by warming, starts to flow from the bottom part of the tank to the upper part through the HXs shell. Thus, the molten salt stratifies in the tank with the formation of the thermocline layers. On the other hand, in discharge mode, the cold oil flows inside the upper heat exchanger in counter-flow with the molten salt at a higher temperature; the salt is cooled and flows towards the lower part of the tank. In this case, the thermocline moves from the upper to the bottom part of the tank. To assess and to characterize this TES concept, ENEA has realized an experimental loop (see Fig. 1b and Fig. 2) able to simulate the real conditions in the CSP plant of Benguerir (Morocco). The operative temperatures are included in the range of 180-300°C. The loop uses the same HTF of the real plant: Delcoterm Solar E15. The tank of the TES prototype has been filled with 5,775 kg of a salt mixture composed of 13.85wt% of $NaNO_3$, 34.63wt% of KNO_3 and 51.52% of Nitcal (KNO_3; $5Ca(NO_3)_2$; $10H_2O$) which, after melting operation, because of the water evaporation, becomes 5,288 kg of salt consisting in15wt% of $NaNO_3$, 43wt% of KNO_3 and 42wt% of $Ca(NO_3)_2$.

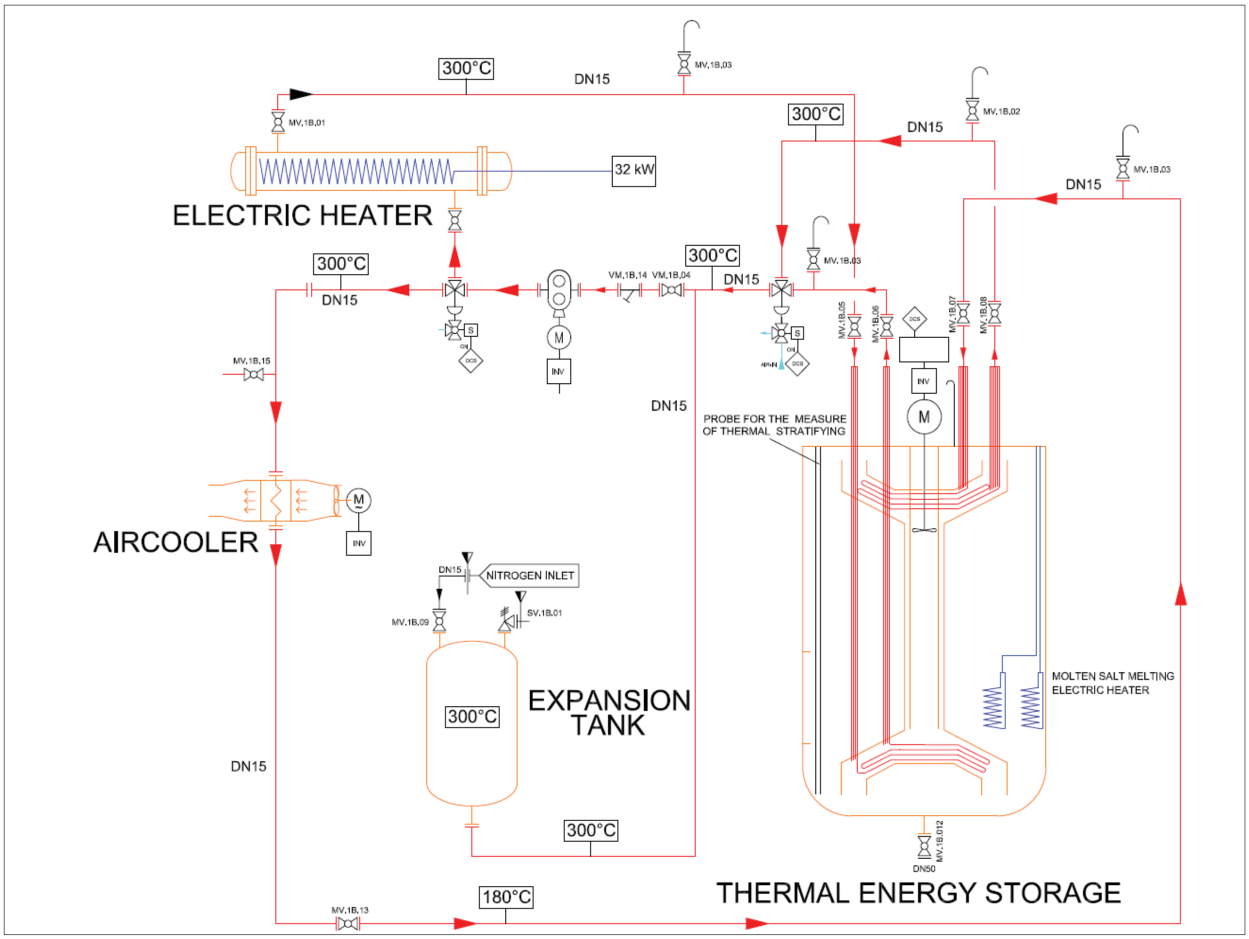

FIGURE 2. Process Diagram of the experimental loop with its main equipment highlighted.

RESULTS AND DISCUSSION

Test in Discharge Mode

These tests have the goal to verify the thermocline effectiveness in discharge mode, namely when the molten salt in the tank is hot and has homogeneous temperature in the whole volume. In particular, it has been checked the stratification of the molten salt depending on its density at different levels and temperature.

Figure 3 shows a synoptic diagram of the TES system and highlights all the detected measures. In order to allow the oil circulation in this mode, it is necessary to set appropriately the 3-way valves EV_VP.1B.01 and EV_VP.1B.02.

The tests, described in the following, differ from the oil speed, the use or not of the mixer MTP.1B.01 and its speed as well as the initial temperature of the salt in the tank.

Concerning the mixer, it is supposed to send the molten salt to the top part of the channel if it is counter-clockwise and to the other way, if clockwise. In this mode, in discharge, it can contrast the natural convection motion, that goes from the upper part, where the temperature is higher, to the bottom part of the tank. If in charge, the impeller works in the opposite way.

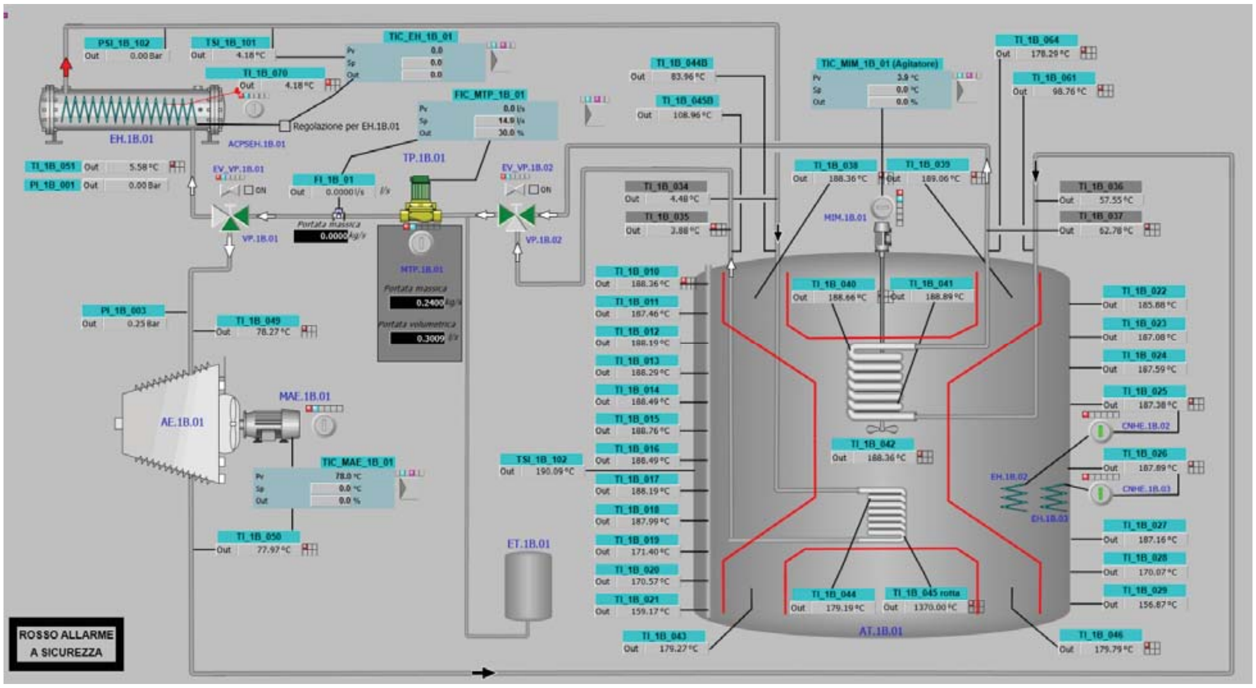

FIGURE 3. Scheme of the coupling CSP-TES-ORC.

Various tests in discharge mode have been carried out. Here, one of them, chosen because full of operative maneuvers has been described, to highlight their effect on the TES. Table 1 reports the initial conditions of the system.

TABLE 1. Initial conditions for the discharge test.

Input	Unit of measure	Value
Initial average temperature of the molten salt in the tank	°C	282.2
Initial temperature at the top of the tank	°C	282.7
Initial temperature at the bottom of the tank	°C	281.7
Initial temperature of the molten salt at the top of the tank channel	°C	282.5
Initial temperature of the MS at the bottom of the tank channel	°C	282.3
Inlet oil temperature set-point	°C	181.0
Oil flow set-point	kg/s	0.165

It is worth to notice that the mixing during the no-working period homogenized the temperatures at the start of the test.

In particular, Figure 4 highlights that the tank bottom level had the same temperature as the other ones; thus, this time, the salt was completely melted.

At minute 28 an oil flow oscillation (see Fig. 5) was detected, and it had some small consequence on the difference between the top and the bottom level temperature into the tank, that decreased.

At minute 45 all the levels in the tank, except for the first one, reached a homogenous temperature again: about 270 °C. Then the impeller was set at 30%: a quick drop of the temperature in the channel was noticed and consequently in oil outlet, up to 253 °C. In particular, the temperature in the top part of the channel (TI_B1_038 and

TI_B1_041) exceeded the one in its bottom part (TI_B1_043). It is so evident that the impeller activation inverted the molten salt flow. So, at minute 57 the impeller was set at 10%, with no apparent effect.

At minute 64 the impeller was set at 10% but in down mode in order to help the natural convective motion of the salt, consequently, the temperature in the channel raised, the higher-level one overcame the lower and a new stratification took place (DT: 6 °C vs 22 °C detected previously), but not enough to ensure the 260 °C in the outlet oil. During this test, the energy [kWh] transferred from the MS to the oil was 58.3 up to the oil pump was active, in addition to other 25.9 up to outlet oil temperature (TI_1B_037) was superior to 260 °C, the limit for the ORC system.

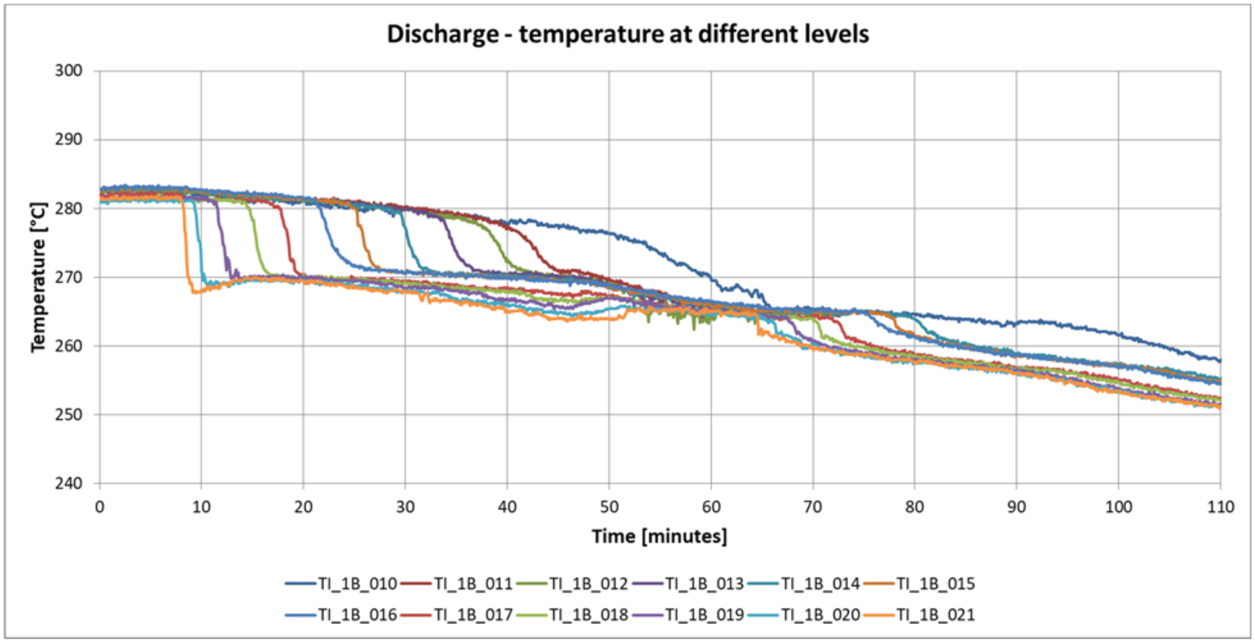

FIGURE 4. Temperature behavior at different tank level in discharge.

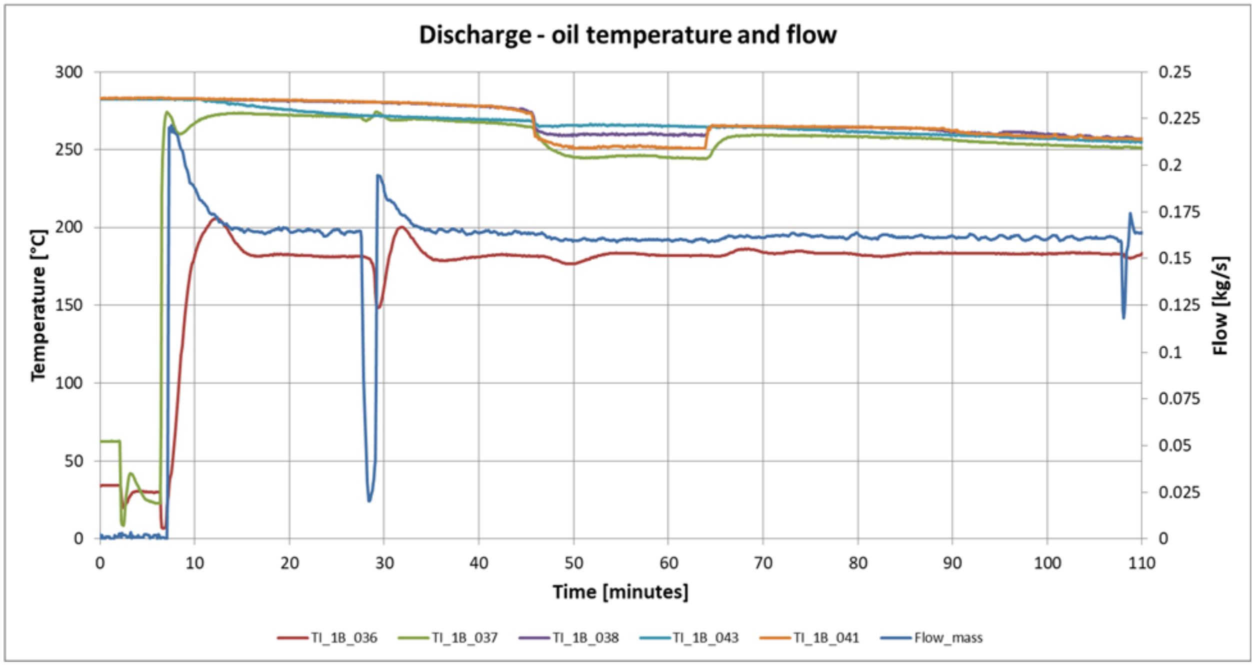

FIGURE 5. Oil temperature and flow behavior in discharge.

Test in Charge Mode

Different in charge tests mode have been carried out. Here, two of them have been described, chosen for the particular initial conditions of the temperature detected in the bottom layers and the use of the impeller. Table 2 and Table 3 report the initial conditions of the system related to the two selected tests.

TABLE 2. Initial conditions for the charge test where impeller was not activated.

Input	Unit of measure	Value
Initial average temperature of the molten salt in the tank	°C	188.3
Initial temperature at the top of the tank	°C	194.9
Initial temperature at the bottom of the tank	°C	158.5
Initial temperature of the molten salt at the top of the tank channel	°C	196.6
Initial temperature of the MS at the bottom of the tank channel	°C	169.9
Inlet oil temperature set-point	°C	290.0
Oil flow set-point	kg/s	0.180

Figure 6, which summarizes the test temperatures, highlights that three initial temperatures in the bottom of the tank (TI_1B_019, TI_1B_020, and TI_1B_021) were lower than the others because this test started from an HSM not perfectly homogenized. However, it is worth to notice that the TI_1B_021 was located under the level interested to the stratification, so all the levels involved in the thermocline process reached the minimum temperature of the higher levels and behaved as expected after a first initial step.

The impeller was never activated during this test. Figure 6 also highlights the stratification, that in this case does not appear very distinct and the temperature difference between the hot and cold layer is about 10 °C.

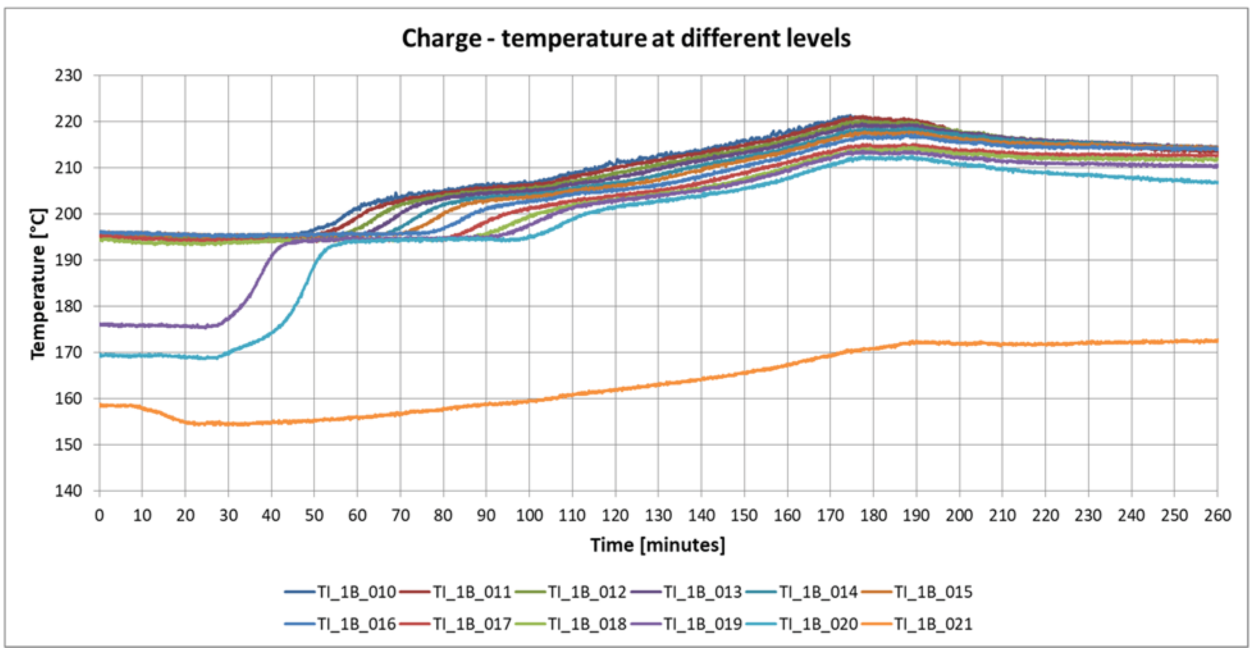

FIGURE 6. Temperature behavior at different tank level in charge mode.

During this test, the energy [kWh] transferred from the oil to the MS was 77.46 in total, namely up to the oil pump was active. Nevertheless, it drops to 29.9 if we only consider the energy exchanged up to outlet oil temperature (TI_1B_0374) was superior to 275 °C. This temperature value, indeed, should ensure 260 °C in the whole molten salt inside the tank. The mentioned energy rises 47.14, considering its change up to outlet oil temperature (TI_1B_0374) was superior to 270 °C, and it becomes 58.52 if exceeded 265 °C.

Figure 7, on the other hand, shows a test where the impeller was activated. It shows a stratification related to the 2 salts levels on the bottom of the tank. The lowest one held this condition until the end of the test, while the other one reached the minimum temperature of the higher levels and behaved as expected.

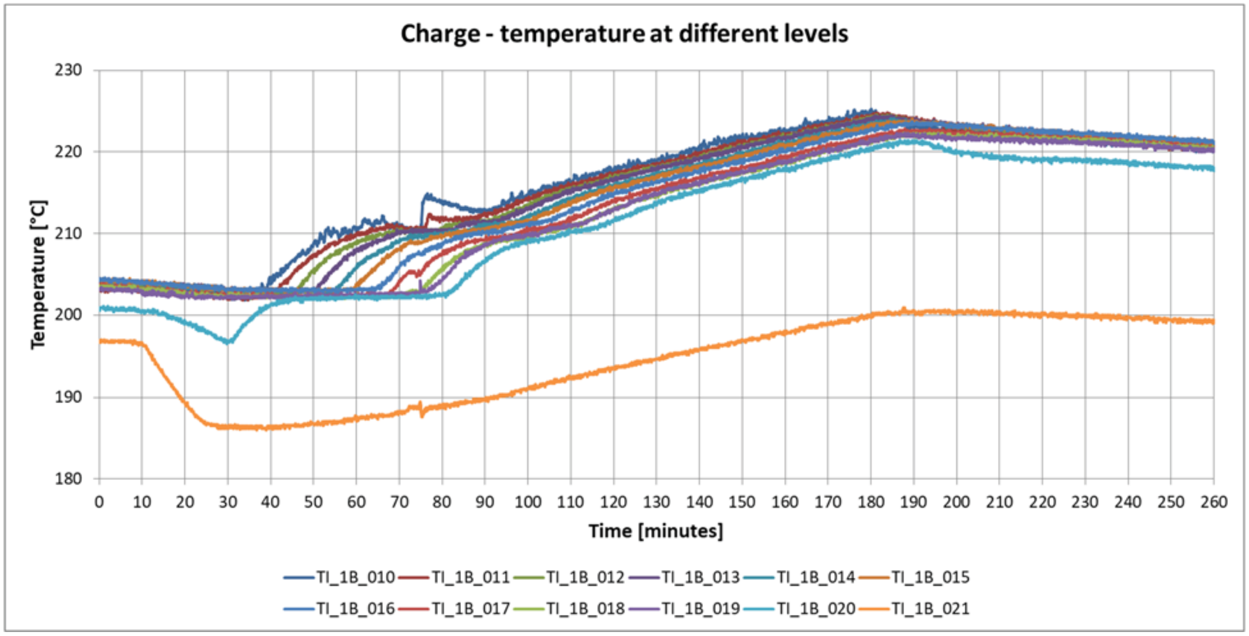

FIGURE 7. Temperature behavior at different tank level in charge mode 2.

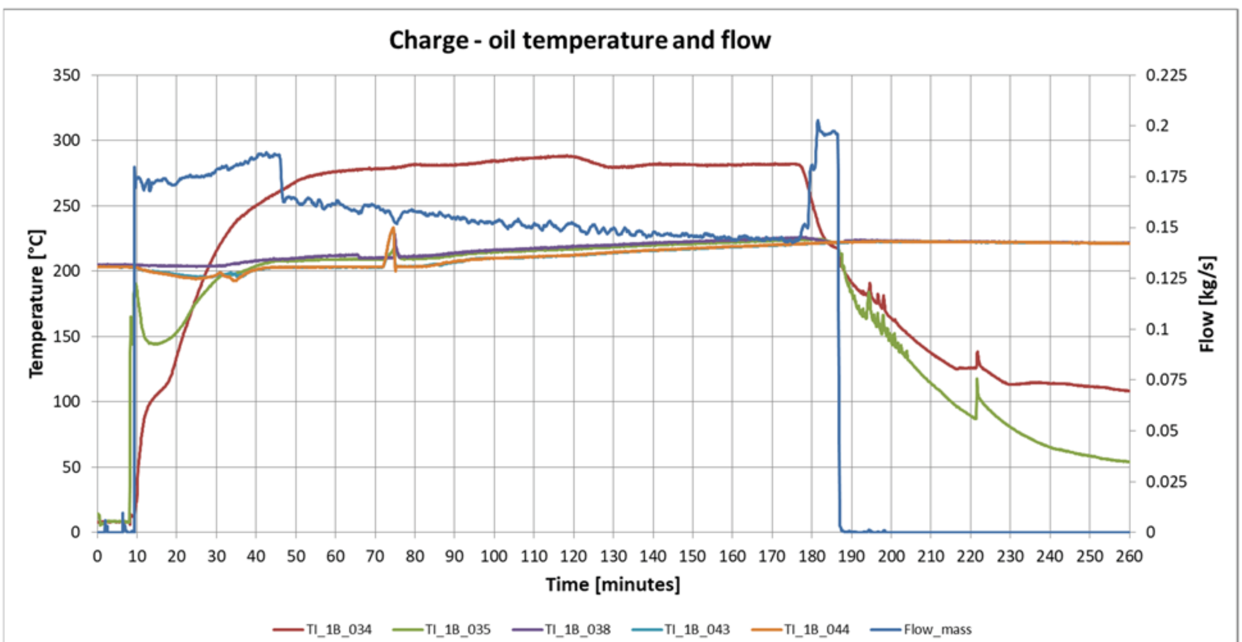

FIGURE 8. Temperature behavior at different tank level in charge mode 2.

At minute 72 the mixer impeller was turned on at 5%: an increase of the temperature difference between the top and the bottom of the salt in the channel appeared. In particular, the TI_1B_043 and TI_1B_044 (Fig. 8) suddenly rose and induced an increase of the salt temperature of the upper levels in the tank (Fig. 7).

Thus the impeller was switched off after about 5 minutes, and the conditions came back as before the perturbation.

By the thermocline effect, the temperature in the salt reached maximum 215 °C and then kept to rise homogeneously, without the expected stratification.

During this test, the energy [kWh] transferred from the MS to the oil was 62.01 up to the oil pump was active, but 54.6 up to outlet oil temperature (TI_1B_0374) was superior to 275 °C which, should ensure 260 °C in the whole molten salt inside the tank.

TABLE 3. Initial conditions for the charge test where impeller was activated.

Input	Unit of measure	Value
Initial average temperature of the molten salt in the tank	°C	203.0
Initial temperature at the top of the tank	°C	203.7
Initial temperature at the bottom of the tank	°C	197.0
Initial temperature of the molten salt at the top of the tank channel	°C	205.0
Initial temperature of the MS at the bottom of the tank channel	°C	203.3
Inlet oil temperature set-point	°C	290.0
Oil flow set-point	kg/s	0.150

CONCLUSIONS

In the field of the TES systems to be coupled with CSP plants, an experimental related to a thermocline system was carried out. It has been executed by a prototype system equipped with a pump and two integrated exchangers, using mineral oil as HTF and a mixture of salts as HSM, consisting of $NaNO_3$, KNO_3 and Nitcal (KNO_3; $5Ca(NO_3)_2$).

The tests highlighted that in discharge mode the thermocline system could ensure the proper temperature for the ORC system production (>260 °C), but never reached the desired temperature of 190°C, needed to discharge the thermal storage system completely. At the other hand, in charge, the maximum temperature obtained by the thermocline is not enough to reach the desired conditions. It was probably due to the too fast speed of the molten salt. In order to delay it, the mixer impeller was installed but did not give the expected results. To summarize, these tests demonstrated the thermocline effect presence both in charge and in discharge mode, but for effective utilization, a new design both of the exchangers and the method to delay the molten salt natural handling is essential. Furthermore, an introduction of a layer able to stabilize the temperature on the top of the tank, like a phase change material (PCM) system should be desirable.

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