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Experimental validation of the innovative thermal energy storage based on an integrated system "storage tank/steam generator"

W. Gaggioli[a], F. Fabrizi[a], P. Tarquini[a] and L. Rinaldi[a]

[a]ENEA CR Casaccia, Via Anguillarese 301, 0123 Rome, Italy

Abstract

In the past years, an innovative thermal energy storage system at high temperature (up to 550°C) for CSP plants was proposed by ENEA and Ansaldo Nucleare: a single storage tank integrated with a steam generator immersed in the heat storage medium. The idea is based on the exploitation of the thermophysical characteristics of the heat storage medium (a binary mixture of salts of $NaNO_3$ at 60% and KNO_3 at 40%) in order to maintain over time, in the single tank, a thermal stratification of the fluid. The thermal stratification is able to trigger, in the immersed steam generator, the natural circulation, shell side and downwards, of the hot molten salt cooled down by the water that flows upwards tube side, thus heating up and producing superheated steam. The advantages of such a system are: - efficient performances; - simple implementation; - compactness: - modularity; - and, overall, contained costs: only one storage tank instead of the two tanks and only one heat exchanger instead of the three exchangers of the classic configuration; reduced quantity of salt; minimization of piping, valves and other components. The technical feasibility of the proposed system, together with the stability over time of the stratification in temperature of the storage medium, have been already verified and assessed. This report has the aim of presenting the experimental results obtained by ENEA in the Casaccia Research Centre (Rome, Italy), with a small scale test section consisting of a 300 kW_{th} steam generator inserted in a 8 m^3 storage tank with molten salt at high temperature. The reported results relate to the behaviour of the system in steady state conditions, and show its promising performances.

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Keywords: Thermal energy storage system; integrated steam generator; molten salt mixture; thermal stratification; stratified mixture.

1. Introduction

An innovative Thermal Energy Storage system, consisting of a single storage tank with an integrated immersed steam generator, has been proposed, developed and patented by ENEA and Ansaldo Nucleare [1] in the past [2,3]:

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this system stores thermal energy by means of the sensible heat of its storage medium (a mixture of 60% $NaNO_3$ and 40% KNO_3). The operation of the integrated system is made possible by the exploitation of the thermal stratification of molten salt due to both its density change with temperature and its low thermal conductivity and high viscosity. It has been already verified by ENEA that the stratification can be maintained quite constant for several hours without mixing [3]. The presence of the immersed steam generator is the active principle that generates, maintains and guarantees the stratification over time. This innovative system has been tested in the last year on the PCS Facility at the Casaccia Research Center of ENEA (Rome, Italy) in the framework of the activities related to the European OPTS Project [4]. A test section consisting of a tank of about 8 m^3 and a 300 kW_{th} steam generator has been utilized for experimental tests in real operational conditions (pressure < 5 MPa, temperature < 550°C). The present paper reports a first assessment about the experimental tests performed on the innovative Thermal Energy Storage system proposed by ENEA.

2. Experimental activity

In the last year, an experimental activity has been carried out to study the behavior in real operational conditions of the new concept of the proposed integrated system (Fig. 1).

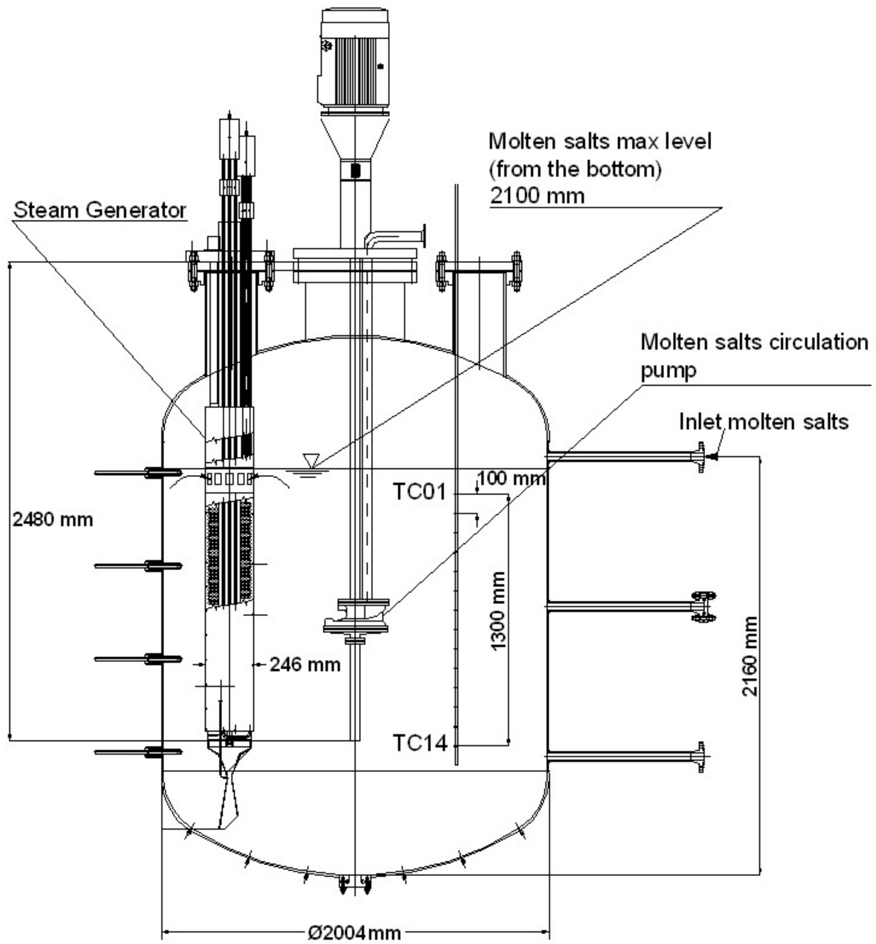


Fig. 1 – Overview of the integrated system “Storage Tank/Steam Generator”

Firstly, some tests have been performed to verify and assess the stratification phenomena which occurs during the discharging/charging phase of the thermal energy in the tank [3]. Subsequently, other experimental tests have been performed to study the behavior of the steam generator itself, and its ability to trigger the natural circulation of the molten salt flowing downwards. Finally, the last experimental campaign has been focused on the assessment and verification of the behavior of the whole integrated system. The experimental activities has been carried out in the last year by ENEA at the PCS Facility, located in the Casaccia Research Centre of ENEA. This experimental facility was realized in 2003 in order to test the solar components of a CSP plant: mainly mirrors, tube receivers, flexible hoses, valves, insulating materials etc.; it uses a mixture of molten salt ($NaNO_3$ at 60% and KNO_3 at 40%) as both heat transfer fluid and heat storage medium, up to 550°C.

The philosophy of the PCS Facility is schematically reported in Fig. 2: a 'single pipe' loop, where the connection pipes between the various components have a suitable slope (5‰) facilitating the filling and emptying of the whole process loop. The molten salt is driven by a vertical centrifugal pump submerged in the storage tank, and circulates through the parabolic collector/receiver system of the solar field where it collects the solar power increasing its temperature up to 550°C; then, it returns to the storage tank.

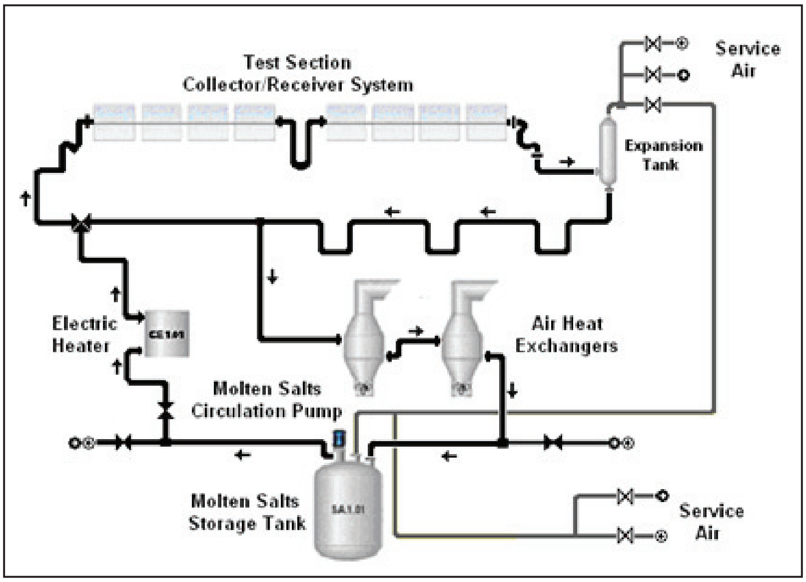


Fig. 2 – Schematic of the PCS Facility

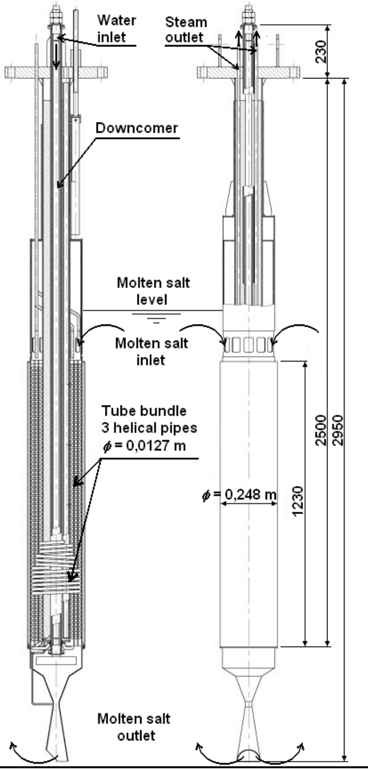
3. Experimental set up

The experiments discussed in this paper were carried on using the main components of the PCS Facility (storage tank (SA101), external electrical heater (CE101) and molten salt pump (Fig. 2)), but to test the innovative thermal energy storage system some modifications to the facility were necessary. The new experimental set up is composed by: 1) a new test section (TS), and 2) a new configuration of PCS's process scheme.

1) The new test section is composed by the storage tank and the molten salt pump of the PCS Facility, a new steam generator of 300 kWth designed by ENEA and Ansaldo Nucleare (Fig. 3) and a rake of 14 temperature probes (thermocouples) at a distance of 0,10 m each other. The new steam generator was inserted into the storage tank through a flange positioned on the top of the tank, that normally was used to insert a flange immersion heater. The immersion temperature probe was used for the measure of the temperature of stratification of the molten salt at different depth levels of the storage tank during the experimental tests.

2) The test section is connected to the loop of the PCS Facility according to scheme of Fig 4. In this new configuration of the experimental facility, the output of the external electrical heater is connected directly with a

new molten salt input of PCS's tank. This input in the tank has been modified to have the inlet of the molten salt in correspondence of the surface of the hot liquid (see Fig. 3). As new input has been used a pipe probe (of diameter of 1” ½) already present and positioned at the right height on the tank wall. The tank has been operated, during the tests, at atmospheric pressure.



The steam generator Test Section		
Nominal power	300	kWth
Tube bundle		
Number of pipe ranks	3	-
Number of pipes per rank	1	-
Number of total pipes	3	-
Downcomer (shared)	1	-
Pipes outer/inner diameter	0,0127/0,0094	m
Arrangement of the pipes	helical	
Transversal/longitudinal pitch	0,0162/0,018	m
Diameter of the external blanket	0,248	m
Length of the tube bundle	1,230	m
Overall length	2,950	m
Thermohydraulic nominal parameters		
Salts inlet/outlet temperature	550/290	°C
Water inlet/outlet temperature	240/520	°C
Water pressure	5,0	MPa
Salts flowrate	0,859	kg/s
Water/steam flowrate	0,123	kg/s

Fig. 3 – Schematic of the immersed Steam Generator

4. Procedure followed during experimental activities

All the experimental tests has been conducted according to the following actions.

In the morning, normally the molten salt stored in the tank already is slightly stratified, consequence of the stratification induced by the test of the day before. The temperature of the higher levels of the molten salt was increased during the night up to the desired value for the test of the day by an immersed automatic electric heater.

At the beginning of the test, the water pump is started and the flow rate is brought up to desired value. The production of steam in the TS begins; the molten salt present inside the shell of the TS begins to exchange its heat with the water that flows tube-side, thus becoming colder and heavier and triggering the natural flow of salt downward. Then the salt, cooled, leaves the TS and collects in the bottom of the tank. In such a way the stratification in temperature of the molten salt inside the tank is rapidly established.

As soon as the thirteenth and fourteenth thermocouple indicate the start of stratification, also the pump of the molten salt is started: the suction inlet of the salt pump is at the bottom of the tank and sucks the cold molten salt. It goes outside and passes through an external helical electric heater where, by Joule effect, it is heated up to the desired temperature for the test; then, it goes back to the tank and enters in it across the aforesaid suitable nozzle at the top level of the stored salt.

When the process is well stabilized, you can see that the stratification very rapidly ceases and all the temperatures recorded by the TCs reach the value of the hot molten salt at the entrance in the tank, except the deepest (the TC n.

14), which remains about at the temperature of the salt at the exit of the TS. The trend of the temperatures (including the exit temperature of the superheated steam) is well defined and is maintained over time for hours if the other independent parameters (flow rates, steam pressure, inlet/outlet temperatures) are maintained in steady conditions over time.

At the end of the test, both the pumps are turned off and all the temperatures tend to stratify while decreasing their values, until the immersed electric heater is switched on to bring the temperature of the salt to the desired value for the test of the next day.

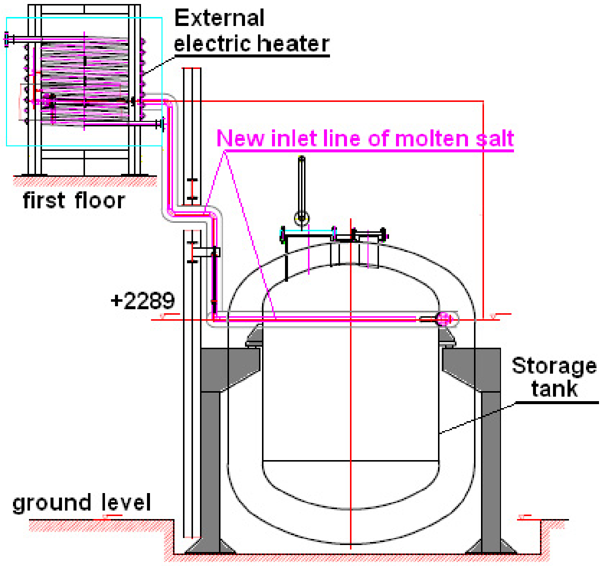


Fig. 4 – The new line of molten salt for the proper entry into the tank

5. Experimental results

The experimental activity consisted in tests about the definition of the operating range of the system in different operative conditions. The nominal working parameters of the SG are: $T_{salts,inlet}$: 550°C; $T_{salts,outlet}$: 290°C; $T_{water,inlet}$: 240°C; $T_{steam,outlet}$: 520°C; $P_{steam,outlet}$: 5.0 MPa; water flow rate: 0,123 kg/s (~420 l/h). Actually, in the tests the maximum water/steam pressure has been 45 bar, due to the possibility of the water loop, readapted for these tests.

In Fig. 4a, 4b and Fig. 5a and 5b are reported the trends versus time of the main thermohydraulic parameters of two characteristic tests, shown as an example, that describe the response of the integrated ST/SG system for two different operative conditions. Test SY8 (Fig. 5a and 5b) was carried out with a molten salt flow rate of ~3,5 kg/s, a water flow rate of ~0,083 kg/s and the water inlet temperature of 240ºC, while the Test SY21 (Fig 6a and 6b) was carried out with a molten salt flow rate of ~5,7 kg/s, a water flow rate of ~0,123 kg/s and the water inlet temperature of 240ºC. All the other experimental tests showed similar trends and behaviours as those reported here.

In both the tests it is possible to observe the rapidity with which also the deepest layers of the molten salt, that at the beginning of the tests were in course of differentiation and stratification in temperature, react at the beginning of the circulation of the molten salt in the tank outside the SG. They rise rapidly to a uniform temperature thus creating a “hot volume” on top, very well separated from the lower cold layers in the bottom of the tank. This fact suggests that it is sufficient to feed continuously the system with hot salt at constant temperature to make sure that the steam production remains constant over time, since the thickness of the hot volume (and, inversely, the thickness of the thermocline zone) does not vary over time.

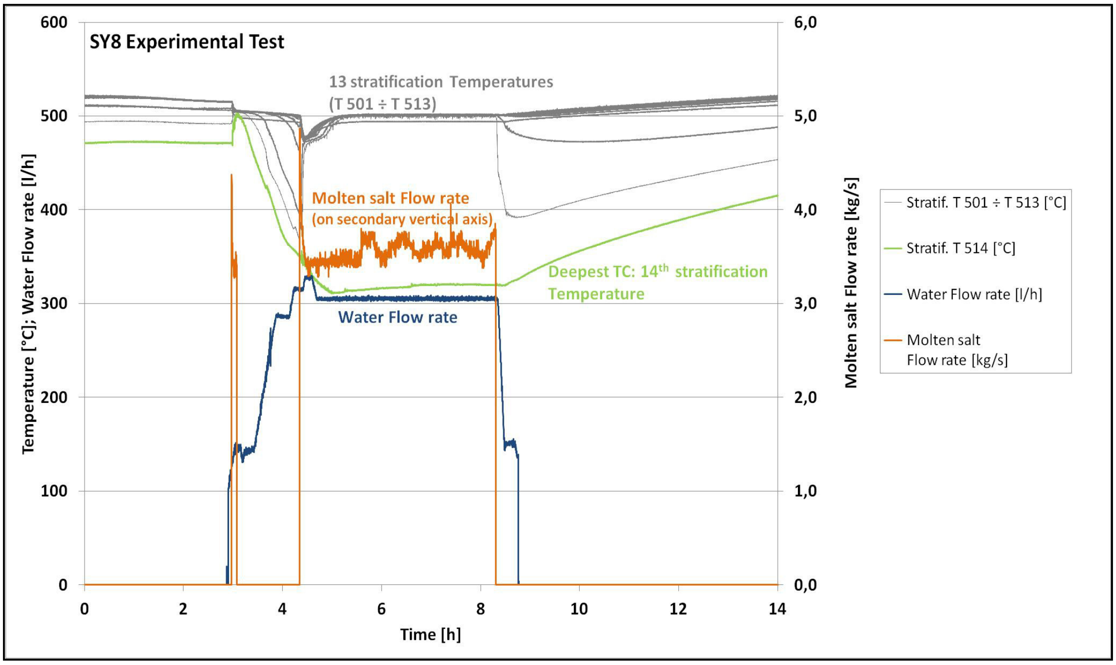


Fig. 5a – Stratification temperatures and flow rates vs time in the SY8 experimental test

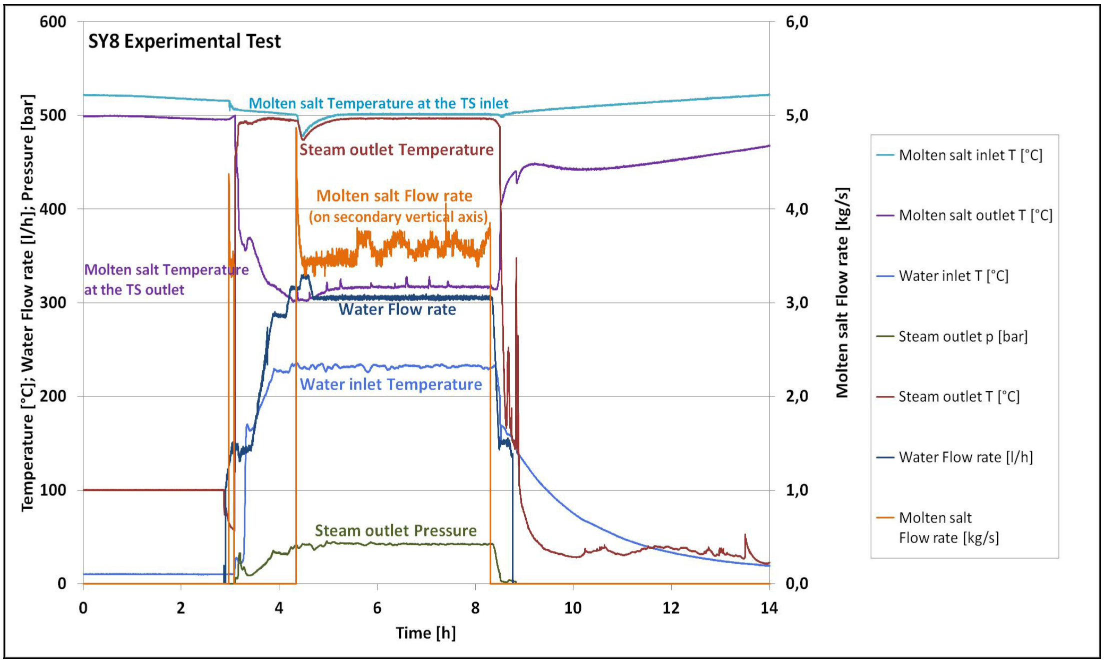


Fig. 5b – Inlet/outlet temperatures, outlet pressure and flow rates vs time in the SY8 experimental test

The small peaks that we can observe in the trend of the outlet temperature of the superheated steam (see Fig. 7, where a zoom of the interested zone of the graph 6b is reported for clarity) probably depend on the fact that the SG's tube bundle is composed by only three concentric helical pipes, whose lengths are necessarily very unbalanced (the outer pipe is 40% longer than the inner one), due to the little size of the SG.

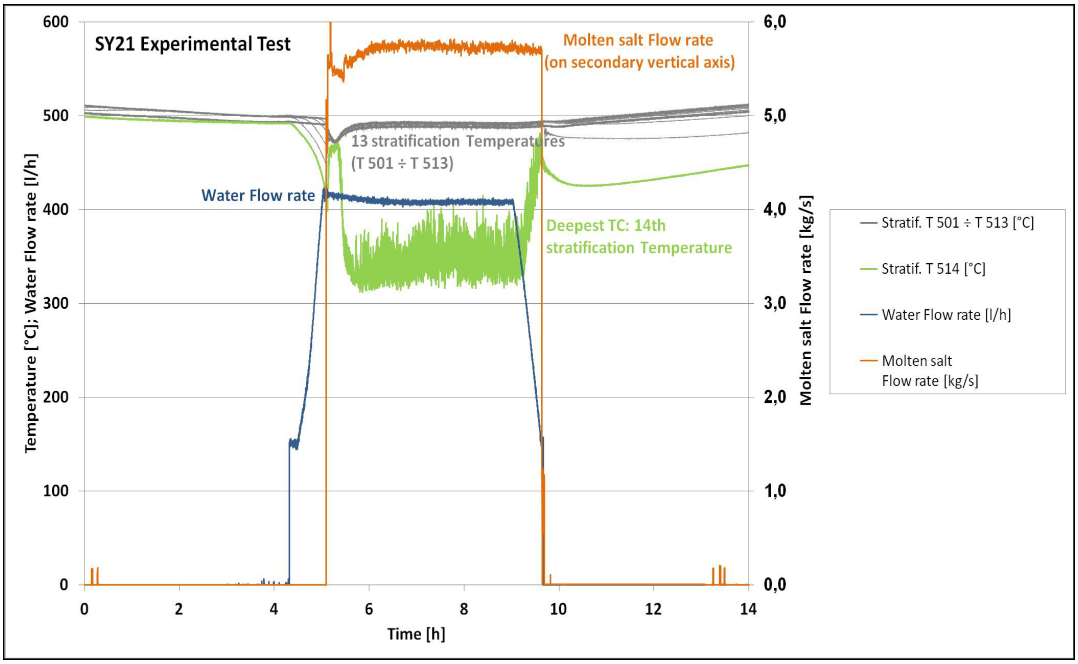


Fig. 6a – Stratification temperatures and flow rates vs time in the SY21 experimental test

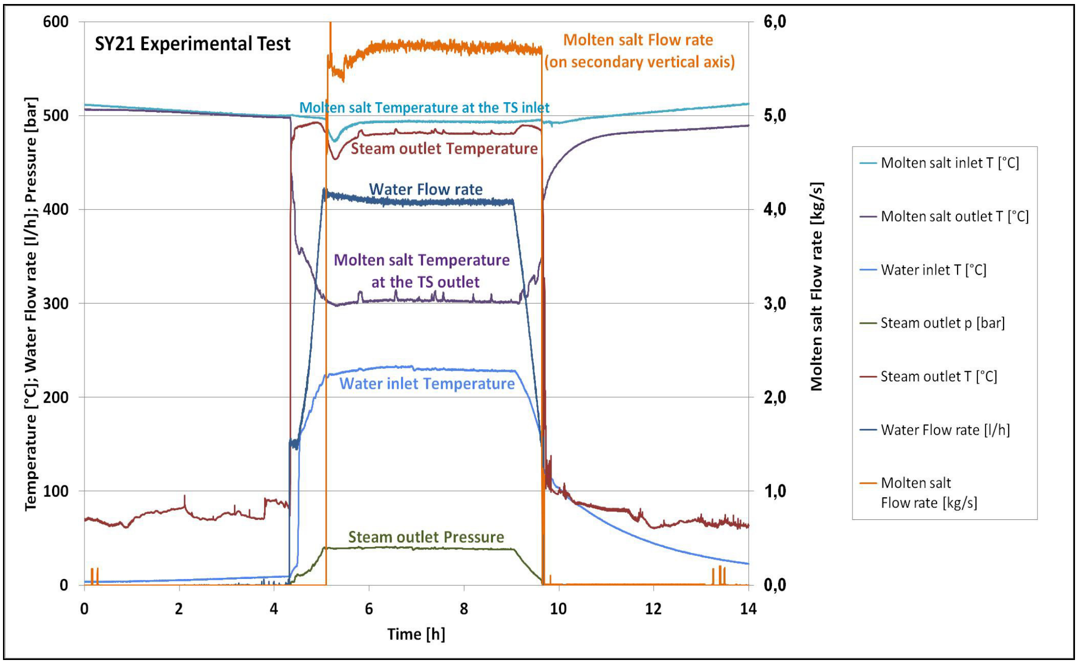


Fig. 6b – Inlet/outlet temperatures, outlet pressure and flow rates vs time in the SY21 experimental test

Thus, sometimes some small instability on the water flow rates of each pipe can be triggered, despite concentrated head losses of suitable values were inserted at the inlet of each pipe to eliminate, or at least minimize, this undesired phenomenon. Note that it is sufficient a minimum instability in the individual flow rates in order to create a non-negligible difference in the values of the outlet temperatures in the three pipes. This behaviour is not present in the bigger SGs, that have tube bundles composed by hundreds of helical pipes with more balanced lengths, and hence more balanced flow rates.

By analyzing the graphs, we can observe that:

- the operational capacity of the ST/SG system to produce superheated steam in steady conditions is verified;
- the stability of the temperature of the produced superheated steam depends primarily, of course, on the stability of the temperature of the hot top level of the molten salt;
- the different behaviour of the 14th thermocouple (the deepest) in the trends of the two graphs is evident: in the second one the trend of this TC is very oscillating respect to the stability of the same TC in the first graph. This different behaviour can be explained by considering the value of the flow rate of the molten salt that enters in the tank: in the second case this value is higher (~ 5,7 kg/s) than in the first case (~ 3,5 kg/s). Thus, the perturbation induced by the high speed of the molten salt in input is propagated till to the bottom of the tank since the hot salt at high temperature, forced against the walls, can reach the lowest levels by slipping along the walls themselves and so influencing the measure value of the 14th TC. This suggests that it is necessary to design very carefully the distribution of the inlet flow of the molten salt in order to prevent a big perturbation of the stratification of the temperature.

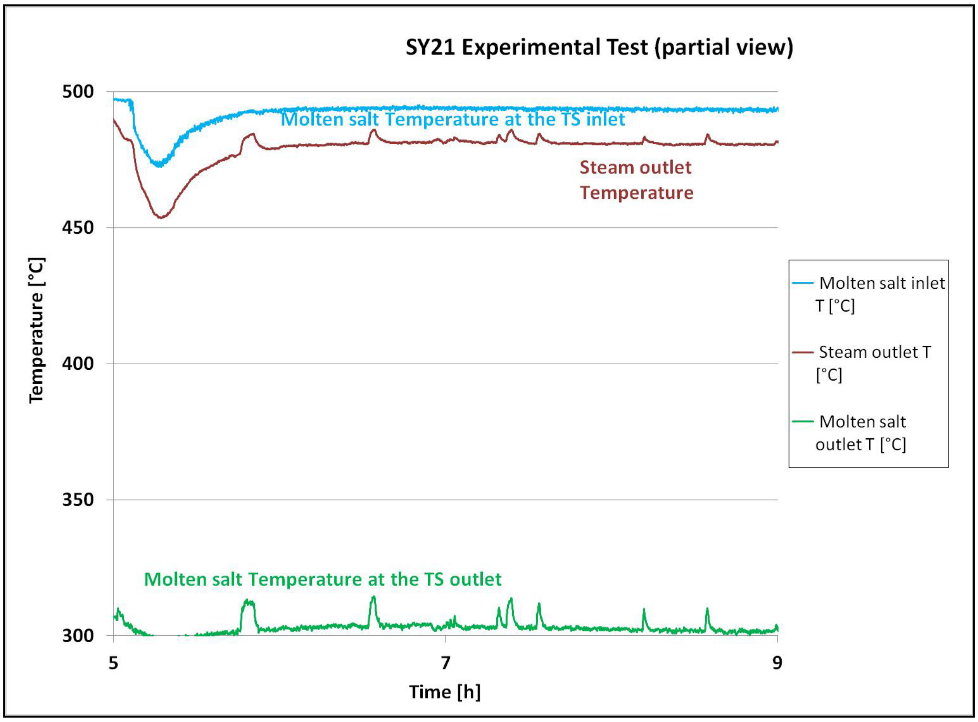


Fig. 7 – Particular of the small peaks in the steam outlet temperature in the SY21 Experimental Test

The operating range of the TS is reported in the next graphs of Fig. 8a and 8b, where the experimental points are shown to give an overview of the operational capability of this test section out of its nominal conditions.

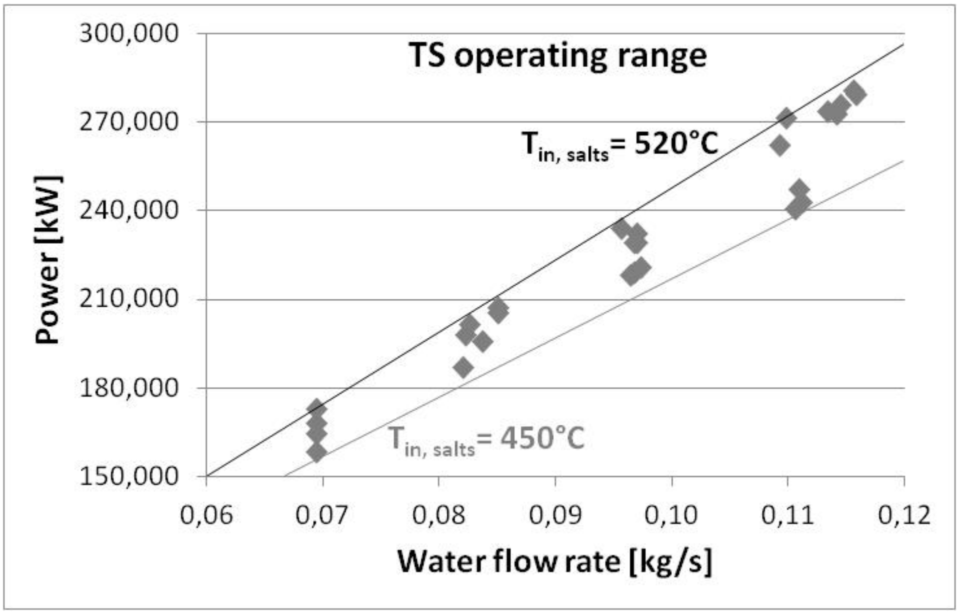


Fig. 8a – Test Section's operating range: power vs. water flow rate

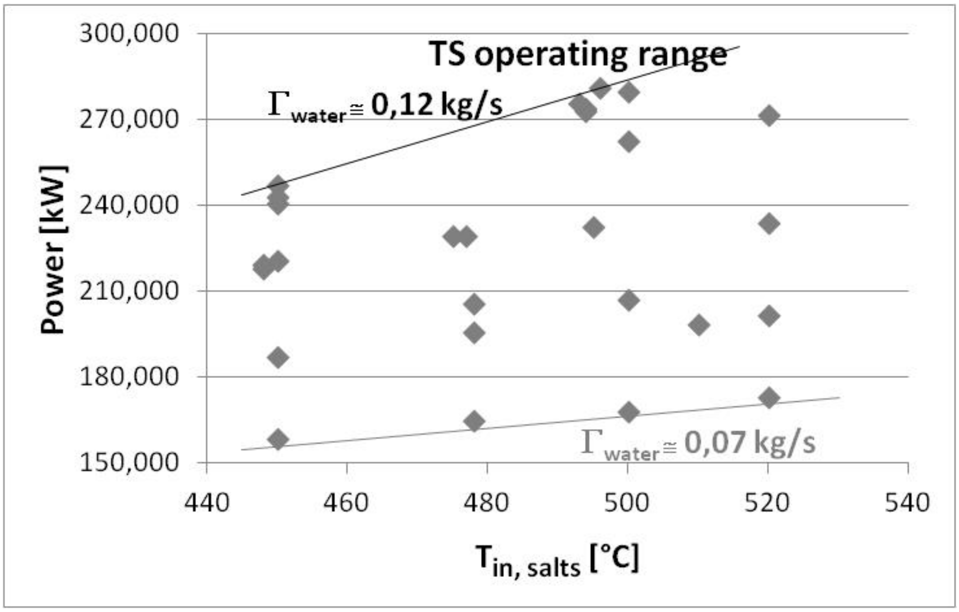


Fig. 8b – Test Section's operating range: power vs. inlet temperature of the molten salts

Due to the maximum operating limit of the tank (520°C), the nominal condition of 300 kWth have never been reached, but in reason of the results already performed with the tests at 520°C there is a reasonable confidence that the TS system can supply the nominal power without problems when operating at nominal conditions.

6. Conclusion

The campaign of experimental tests performed on the TS, that reproduces in small scale the proposed integrated ST/SG system, allow to say that it is worthwhile to carry on the studies on this system. It can be a good alternative to the "classic" solution of two storage tanks and an external SG, by the point of view both of the continuous production of superheated steam and also primarily of the possible saving of components, management and economic.

It is necessary to deepen the research overall by testing a component in a bigger scale, possibly in industrial scale, in order to obtain all the necessary data about: - its performances over time at every power regime in steady/transient state and during thermal charge/discharge phases of the tank; - its behaviour in normal/abnormal or accident operations; - its functionality during start-up and shutdown; - its maintenance operations, and so on.

The current experimental results, together with the experience made in the management of the TS reproducing the SG, are functional to obtain useful information for the design of the system in larger scale (12.5 MW_{th}) to be tested in the second phase of the EU OPTS Project.

From the technical point of view, the direct observation of the operation of the SG during the experimental tests and the analysis of the experimental data suggest that the next efforts for the design of the large scale ST/SG system with a single tank must be prioritarily focused on the following aspects:

- the distribution of the hot molten salts at their inlet in the tank;
- the length of the tubes of the tube bundle, in order to minimize the possible instability of their flow rates;
- the minimization of the overall length of the SG and its position in the tank, that should be as higher as possible in order to maximize the effect of the hydrostatic drive of the molten salt' "cold leg";
- the volume of the molten salt stored in the tank, which depends on the operating time in hours required for the production of superheated steam in the absence of a continuous charge of thermal energy.

Other desirable efforts are to be made in the development of suitable mathematical/physical models and computer codes, able to verify and assess this integrated system. In ENEA this task is already at good point.

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