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Energy Procedia 49 (2014) 780 – 789

Energy Procedia

SolarPACES 2013

An innovative concept of a thermal energy storage system based on a single tank configuration using stratifying molten salts as both heat storage medium and heat transfer fluid, and with an integrated steam generator

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Abstract

The proposed innovative thermal energy storage system is based on a single tank containing a mixture of nitrate salts (60% $NaNO_3$ and 40% KNO_3 in weight; this mixture gradually changes from solid to liquid in the temperature range between about 220°C and 240°C, becoming completely melted above this temperature), with an integrated steam generator directly contained inside it. The system is operated exploiting the thermal stratification of the salts mixture in the temperature range between 550°C (hot temperature) and 290°C (cold temperature). The experimental work conducted at ENEA has revealed that the thermal stratification of the molten salts mixture can be maintained quite constant for several hours and the presence of the integrated steam generator actively guarantees and maintains the stratification during the operation time, avoiding mixing of the stratified layers. The single-tank system with stratification of the molten salts and an integrated steam generator is an important improvement in terms of efficiency, reliability and cost reduction, with respect to the two-tank thermal energy storage system. This report has the aim of giving an overview of this new technology but, given the fact that the experimental activities are still ongoing, the description of the system remains at a qualitative level. The complete set of experimental results will be presented in the future when the Projects that are framework of this research will have been completed.

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: thermal energy storage system; integrated steam generator; molten salts mixture; thermal stratification; stratified mixture.

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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.2014.03.085

1. Introduction

In the context of the renewable energies, which are mostly characterized by the volatile and unpredictable nature of the energy source, the ability to store the collected energy and deliver it during the periods of absence of the source itself, is one of the most important requirements..

Among the different renewable energy technologies, an evident advantage of the Concentrating Solar Power (CSP) technology is the possibility to use relatively cheap Thermal Energy Storage (TES) systems to store directly the collected solar thermal energy. The most popular option consists in a suitable Heat Storage Medium (HSM), well insulated against thermal losses, which is kept for a long time at the high temperatures generated by the concentrated solar radiation.

Each different TES concept aims at collecting energy in order to delay its delivery time, or to smooth out the plant output during intermittently cloudy weather conditions. In this way the dispatchability of energy by a CSP system can be extended beyond the periods of absent solar radiation, also minimizing the need to burn fossil or renewable fuels in case of hybrid or backed-up systems.

A great variety of TES options are considered today worldwide. Our proposal is an innovative solution of TES for the next generation of solar plants that intends to provide an efficient, reliable and economic energy storage for CSP plants.

The two-tanks system is currently the most widespread in the world. In this case, the HSM is maintained at the two different operative temperatures in the two different tanks. Besides the solar field, the Storage Tanks (STs) and the Steam Generator (SG) are the two main components of a solar power plant. The integration of these components inserting a once-through SG inside a single tank can potentially bring a remarkable simplification of the loop (and of the plant management) that consequently leads to a reduction of costs. The single-tank system with integrated SG reduces the HSM volume and the costs lowering the number of components from the three of a conventional shell-and-tube SG (pre-heater, evaporator, super-heater) to only one.

However, in a single-tank system it is difficult to separate the hot and cold HSM but because of the density difference of the fluid contained in the tank, the HSM naturally stratifies from coolest layers at the bottom to warmest layers at the top.. In the case of use of a mixture of molten salts as HSM, the characteristic physical properties of the molten salts themselves are exploited: the stratification is obtained and maintained thanks to the low value of their thermal conductivity: in fact, due to this low value, the salts behave like a thermal insulator preventing the heat conduction from a layer of the salts to another, which is not the case, for instance, when dealing with liquid metals of nuclear fast reactors. On the other hand, the convection induced by the thermal losses to the ambient can be greatly reduced by means of a good insulation, positioned both externally and internally (patent ENEA/KTI in course of registration) to the tank, in such a manner that the stratification can be maintained for many hours. Moreover, the integrated SG acts as the active element that maintains the salts stratification.

1.1 Direct molten salt heat transfer/storage fluid

The use of molten salts mixture in both the solar field (as HTF) and thermal energy storage system (as HSM) eliminates the need for expensive heat exchangers between two different process fluids. Moreover the solar field can be operated at higher temperature compared to the use of oils as HTFs. This combination also allows a substantial reduction of cost of the TES system, since for a constant amount of stored energy, a higher temperature of storage leads to a reduction of the tank volume. Unfortunately, molten salts freeze at relatively high temperatures (120 to 240°C (250 to 465°F), depending on their composition) and special care must be taken to ensure that the salts do not freeze in the piping of the solar field during the night or during periods of lack of sun or maintenance.

ENEA has proven the technical feasibility of using a molten salts mixture (60% $NaNO_3$ and 40% KNO_3 in weight, changing from solid to liquid in the temperature range between about 220 ÷ 240°C, becoming completely melted above this temperature [1]) in a parabolic trough solar field by its experimental facility PCS in the Casaccia Research Centre (Rome, Italy). The concept has been demonstrated at industrial level by ENEA and its partner ENEL in the power plant located near Priolo Gargallo (SR, Sicily, Italy), where a direct two-tanks system utilizing the aforementioned salts mixture was installed to generate 5 MW of electrical power.

2. The TES/SG new concept

The proposal concerns the innovative concept of a TES system based on the single tank configuration using stratifying molten salts as both HSM and HTF and with an integrated SG (patent registered, [2]).

Despite the difficulties connected with the management of a high temperatures fluid, the use of the molten salts mixture as process fluid (both heat transfer and storage fluid) in the thermodynamic solar plants could become a good opportunity if their peculiar characteristics are favoured and utilised for the scope, instead of countered.

A clear example can be found in the case of the proposed TES/SG subsystem, where the exploitation of the peculiar characteristics of the mixture is at the basis of the idea of developing a single storage tank with the molten salts stratify in temperature.

The use of a single tank is an evolution of the concept of double-tank storage (the "hot" tank and the "cold" one, widely used in the CSP plants); this evolution was conceived and designed to make CSP installations simpler, cheaper and more manageable; the single-tank concept only requires that the contained fluid stratifies in temperature; inside the tank a SG is submerged, that is composed by a once-through countercurrent heat exchanger with helical tube bundle where shell-side, in an annulus shaped channel, the molten salts flow in natural circulation from the top to the bottom of the tank by gravity, and tube-side the water flows upward absorbing the energy (heat) stored in the tank and becoming superheated steam. The motion of the hot fluid is initiated by the fluid layers in contact with the colder tube bundle: while being cooled down, the molten salts become heavier, flowing downwards and triggering a natural motion. The molten salts stratification phenomenon begins naturally and is maintained over time by the presence and the operation of the SG. In addition, the hot fluid, due to its characteristic thermo-chemical-physical properties (it is a binary mixture of salts that presents a very low thermal conductivity: ~ 0.5 W/m°K), tends to maintain the stratification, in the absence of perturbative phenomena of its state. Indeed, the very low value of its thermal conductivity does not facilitate the conductive heat transfer through the different layers of fluid at different temperatures, that is the case, for instance, when dealing with the molten metals usually used in nuclear fast reactors. As a matter of fact, in this last case, such a fluid never tends to stratify since its high thermal conductivity (~ 16.5 W/m°K, i.e. more than 30 times that of the molten salts) would counteract the formation of a possible stratification letting a rapid transfer of heat transfer from one layer to another. In our case, instead, the only necessity is to avoid as much as possible the trigger of perturbative motions by means of a suitably designed inlet, e.g. a distributor of flow that allows a soft inlet of the hot molten salts coming from the solar field in the top of the tank, and also by minimizing the thermal losses to the ambient in order to avoid the establishment of a homogeneous temperature distribution due to convection. This last task can be achieved, with a good insulation design of the external wall of the tank, for example exploiting once again the characteristics of poor heat conduction of the mixture of the salts in such a way that a small layer of about ten/twenty centimetres of liquid salts is locked in appropriate cavities made on the whole inner wall of the tank (patent pending); the eventual freezing of this stationary layer of salts in any case would not implicate any significant problems for the regular operation of the entire system. Another characteristic property of the molten salts favours the maintenance of the stratification against the homogenization of the temperature due to convection: the dynamic viscosity of this fluid increases its value about 60% going from 550°C to 290°C [1], making more difficult the mass movement from the cold layers towards the hotter ones.

The OPTS Project [3] (in the frame of the European 7^{th} FP) is a 3 years experimental program focused on the full development of this system, hereafter referred to as TES/SG, up to demonstration level.

The main features of this type of storage tank with integrated steam generator system are:

- SG realization with helical coils (implementation borrowed from nuclear applications);
- 'once-through' configuration with direct steam production at the required quality (also superheated);
- some predictable advantages:
  - possible salt freezing in distribution heads avoided;
  - high thickness shell (for steam high working pressure) avoided;
  - possibility to maintain warm the SG during a plant stand-by ;

- safety advantages: in case of a pipe failure with water/steam leakage in the tank, accident does not give serious consequences, if the tank (working at atmospheric pressure) dome and the vent pipes are suitably designed, also because the mixture of molten salts do not react with water;
- intrinsic modularity of the system;
- possibility of system maintenance by operating from the top of the tank.

The integration with the SG can be realized in two different ways:

- the first one is very innovative: the SG is positioned directly into the tank (Pool-type) where it carries out the molten salts stratification, and it operates with a shell-side natural recirculation of the molten salts, with a drastic simplification of the process loops and with a more compact and manageable device, so avoiding external piping systems and pump; this concept is the least expensive;
- the second one is an external (Loop-type) shell-and-tube once-through SG, with respective piping system and pump, always working with natural recirculation of the molten salts that helps to establish the stratification of the salts mixture in the tank, even if it gives fewer advantages in terms of reduction of pipes, components and costs.

These SGs, of both types, are foreseen to be of modular type and can be used in n-multiple units, either inserted in larger tanks for the Pool-type (Fig. 1) or distributed around them for Loop-type to fit the rated power of bigger solar CSP plants.

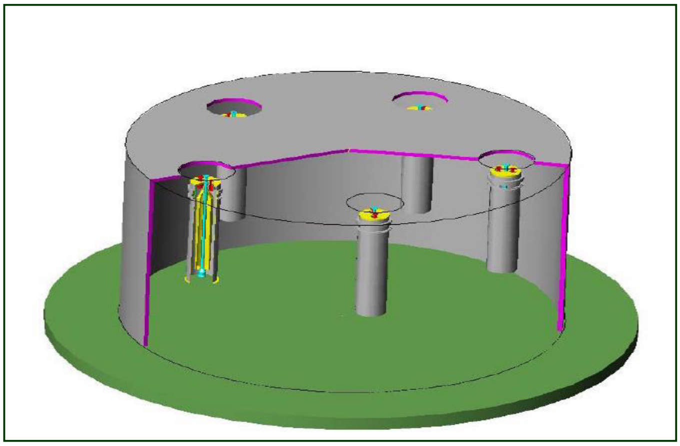

Fig. 1. – Schematic of a 125 MW_{th} TES/SG in a possible Pool-type configuration (5 SGs of 25 MW_{th} each)

It is worth to highlight that this TES/SG concept has been initially considered in the experimental activity carried out by ENEA in cooperation with ANSALDO [4], in the frame of the national Italian Project "EliosLAB". In this project a whole TES/SG system of large size, i.e. for a 50 MWe CSP plant (see Fig. 1, picturing n. 5 SGs immersed in a big storage tank) was already defined and preliminarily designed; the basic design of one modular 25 MW_{th} SG was outlined. Today, the experimental assessment of its basic concepts/performances is in progress at the Casaccia Research Centre of ENEA (Rome, Italy), on small scale mock-up consisting of a 300 kW_{th} SG inserted in a 8 m^3 molten salts storage tank.

With this little tank, some years ago the first experimental data on the stratification of the mixture of molten salts were collected. An example of the behaviour of the salts mixture over time is shown in the graph of Fig. 2, reporting the results of one of the experimental tests: it can be seen that the stratification established at the beginning of the test was maintained over time for several hours without establishing phenomena of mixing of the layers, even with the losses of heat towards the ambient, The tags of the thermocouples that measure the temperatures are reported in the graph: looking also at Fig. 3, where the positions of the thermocouples are roughly indicated, the intermediate trends correspond to the thermocouples positioned in the air cushion over the upper level of the salts.

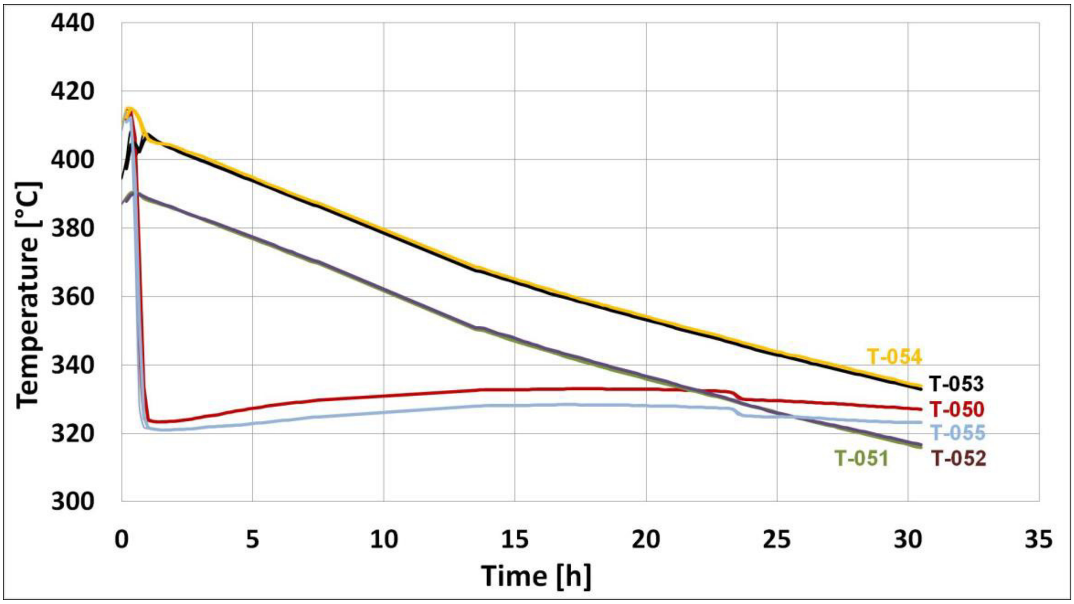

Fig. 2. Experimental data of a stratification test carried out in the tank of the PCS facility

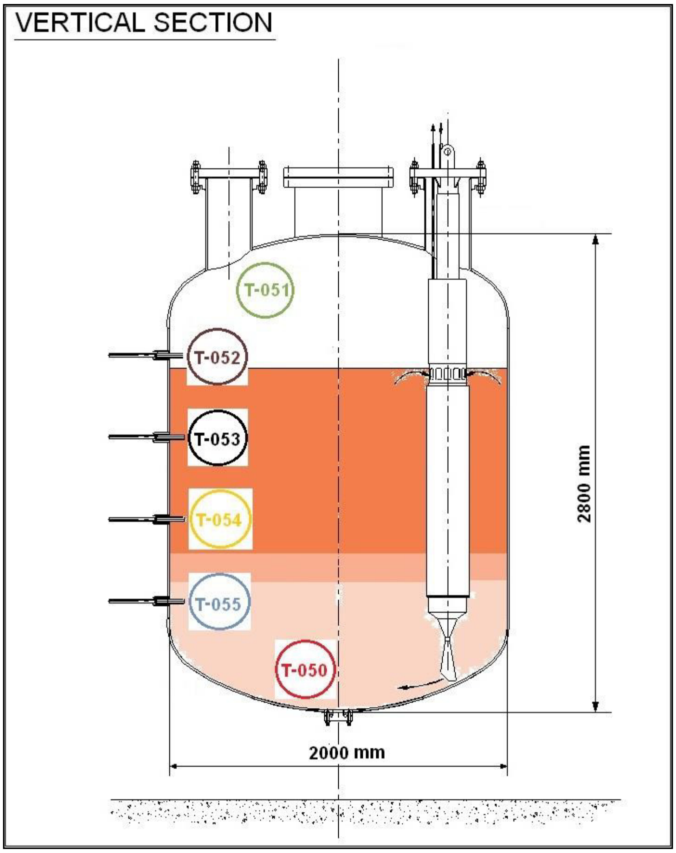

Fig. 3. – Position of temperature measurements in the PCS tank

The stratification does not disappear so easily due to the natural convection induced by the thermal losses to the ambient, since we can observe this behaviour also after 10 ÷ 15 hours. Moreover, the tank where this test has been performed has very small linear dimensions (d= 2.0 m; h= 2.8 m) and, for bigger tanks, the phenomenon of thermal losses will be smaller thanks to the different volume/surface ratio.

We also want to emphasize that that this behaviour of the molten salts stratification much more is established when the SG is immersed in the salts of the tank, since it acts as an active element in the creation and in the stabilization of the temperature stratification. The experimental facility is represented in Fig. 4, where the tank with the integrated/inserted 300 kW SG and the positions of the thermocouples used to measure the temperature of the stratified layers are shown. There are n. 14 thermocouples (every 0.1 m) arranged on a “comb-shaped” tube, immersed from the top into the mass of the molten salts.

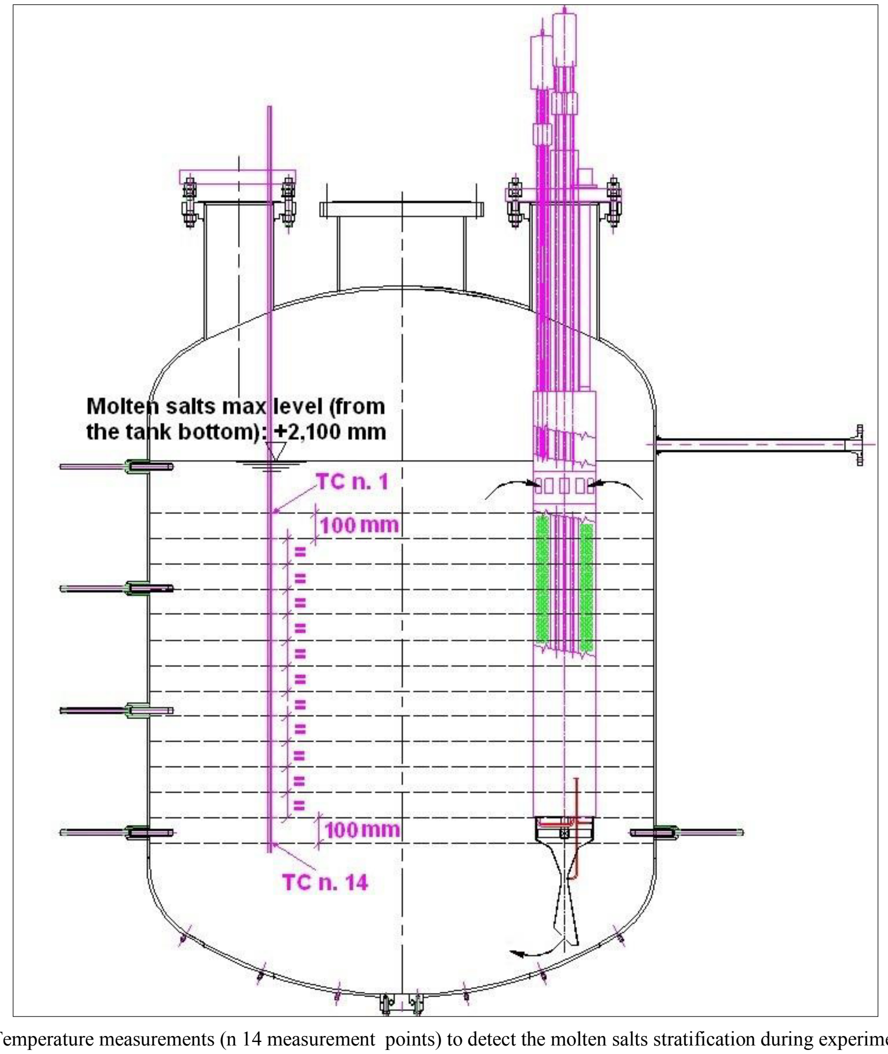

Fig. 4. – Temperature measurements (n 14 measurement points) to detect the molten salts stratification during experimental tests

Fig. 5 shows the behaviour of the temperatures of the different salts layers measured by the 14 thermocouples in the mass of the molten salts mixture in the tank of the PCS experimental facility, during an experimental test of discharging heat with initial salts temperature at 500°C; the measurement of the water flow rate in the tubes of the SG is reported (FI_7003), as well on the second Y-axis. Each experimental point is acquired by the Data Acquisition System every 5 seconds.

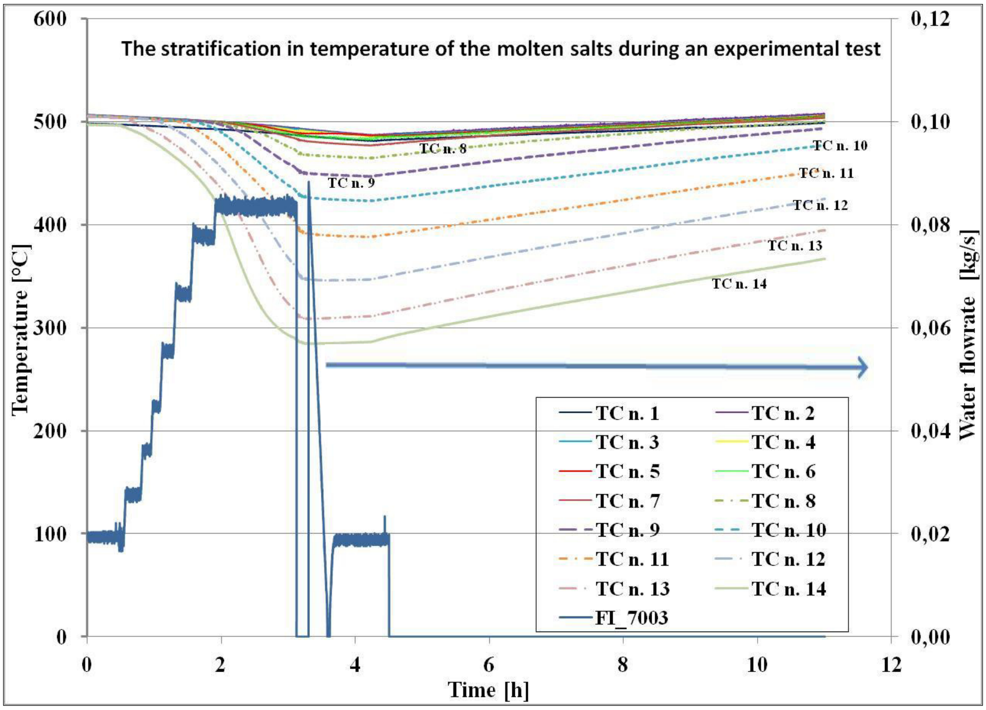

Fig. 5. – Trends of the 14 temperatures and of the water flow rate during an experimental test

We can see that, when the SG begins to operate and to exchange heat with the molten salts (~0.5 h), the mass of the molten salts contained in the tank begins to be cooled down since the salts get out cold from the SG outlet in the bottom of the tank.

Since the system is closed, i.e. it is in conditions of "thermal discharge" of the tank because the salts do not recirculate outside and they are not heated and reintroduced to the higher warm level, the entire system tends to cool down maintaining a stratification which increases in height over time, since the SG continues to operate subtracting heat from the system and the lower layers of salts over time tend to cool. At point ~ 3 h the water pump is stopped, the electrical heater inside the tank begins to operate and the temperatures of the different layers of the salts begin again to rise and tend to reach the previous values, that will be achieved during the night.

These two examples (Figs. 2 and 5) give an idea of the possibility to create a stratification in the molten salts stored in the tank, and also (fig. 5) that a SG inserted in the tank behaves like an active element that enhances this phenomenon. The hot/cold transition zone is named the "thermocline" zone, and its characteristics and behaviour (height, upward and downward shift during the phases respectively of discharging and charging heat etc.) will be assessed by suitable experimental tests.

3. Economic considerations

To have an idea of the dimensions and costs of the storage tank for the proposed configuration, let us do few calculations: the amount of molten salts volume associated to a SG depends on the number of hours of operation of the SG itself. So, if we consider for example a 25 MW_{th} SG operating for6 hours, we need to store in the tank a thermal energy Q = 25 x 6 = 150 MWh_{th} = 540,000 MJ. Since the specific heat of the molten salts mixture is c_{psalts} $\cong$ 1.5 kJ/(kg °C), with a ΔT_{salts} = 260°C [550°C - 290°C], the needed molten salts mixture mass is:

$$M_{salts} = Q/(c_{p,salts} \times \Delta T_{salts}) = 1{,}385{,}000.00 \text{ kg}. \qquad (1)$$

This quantity corresponds, for a density of the salts mixture $\rho_{salts} \cong 1{,}800$ kg/m³, to a volume of molten salts mixture $V_{salts} \cong 770$ m³ dedicated to such a SG, that is a tank of approximately D= 12 m and H= 7 m.

To get an idea of the costs, we can refer to Table 1, which summarizes the costs estimated for the Test Section proposed in the OPTS Project [3], that is a 50 MWh_{th} integrated system Storage Tank + Steam Generator. In the same table, these values are compared to the costs (2^{nd} column) of a typical solar plant with a “two-tanks” configuration, that is to the costs of the ARCHIMEDE facility that was built in 2010 by ENEL, an Italian utility, in Priolo (Sicily, Italy), a demonstrative facility designed by ENEA in cooperation with ENEL. The values for OPTS Project are extrapolated to the same mean daily stored energy of ARCHIMEDE Project (that is 80 MWh_{th}/d instead of 50 MWh_{th}/d, with a ratio of $\sqrt{1.6} \cong 1{,}3$), and thus the corresponding costs are multiplied by 1.3.

Table 1. Comparison of the costs of the TES/SG systems in OPTS and ARCHIMEDE Projects.

	OPTS Project		***ARCHIMEDE Project***	
	Storage Tank			
	unit	€	unit	€
Number [-]	1	910,000.00	2	1,800,000.00
Molten salts (1.8 k€/ m³)	420 [m³]	756,000.00	634 [m³]	1,140,000.00
Pumps n.	1	350,000.00	1	350,000.00
Foundations (with cooling system) [€]	-	286,000.00	-	572,000.00
Bearing metallic structure	1	150,000.00	2	200,000.00
Refractory and insulation	1	100,000.00	2	200,000.00
Auxiliary electric heating system	-	100,000.00	-	200,000.00
Total [€]		2,652,000.00		4,462,000.00
	Steam Generator			
Position	internal		external	
	unit	€	unit	€
SG sections n.	1	500,000.00	3 (pre-heater, evaporator, super-heater)	1.200,000.00
Total weight (s.s.) [t]	5	0	24	0
Bearing metallic structure	already considered above	0	1	150,000.00
Primary (salt) pumps n.	1 (impeller)	40,000.00	1	350,000.00
Primary (salt) piping [t]	-	0	4	160,000.00
Primary (salt) valves n.	-	0	6	0
Secondary (water) valves n.	2	50,000.00	6	150,000.00
Refractory and insulation	-	0	3 (SG sections)	100,000.00
Auxiliary electric heating system	-	0	3 (SG sections)	100,000.00
Total [€]		590,000.00		2,210,000.00
	Instrumentation and Controls			
Instrumentation and Control (5%)	-	162,000.00	-	333,000.00
Grand Total [€]		3,404,000.00		7,005,000.00

By examining the Table 1, it can be seen how convenient is the use of the proposed system compared the ”two tanks” system in terms of saved materials and other costs.

Of course, in the future the costs will be lower than those calculated, also because Table 1 refers to a Test Section, that is certainly more expensive due to the singularity of its design and construction. Moreover, an important point to be considered is that the possible spread of this type of system, which would follow the diffusion of this configuration of solar thermal power plants, can anyway lead to a reduction of the costs evaluated according to the previous curves of Fig. 6, where costs are reported versus the number of the facilities already realized [5].

From [3], to evaluate the up-scaling to commercial scale (125 MW_{th}) of the integrated ST/SG system, it is worth to both estimate the forecasted costs of the proposed full-scale system, i.e. the Storage Tank with the five SGs, and to compare it to an usual system with two Storage Tanks and one external SG that is normally composed by three sections (pre-heater, evaporator and super-heater).

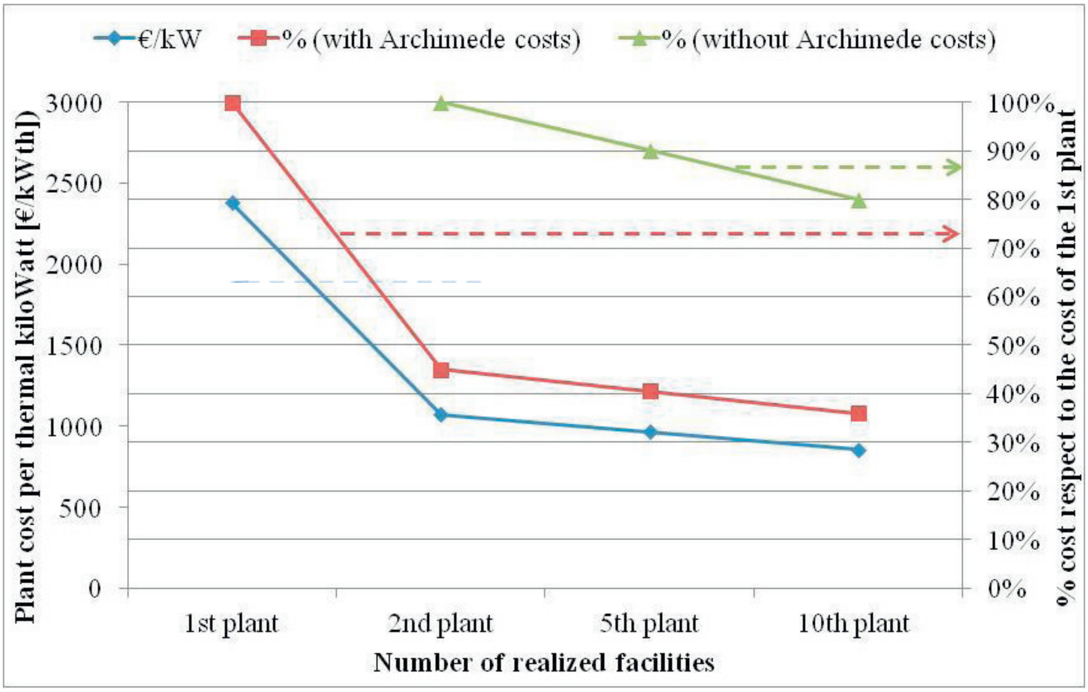

Fig. 6. Learning curve reporting the possible decrement of plant cost versus the number of plants realized

In order to determine the cost of the proposed full scale (125 MW_{th}) system using the previous values of Table 1, we adopt a simplified expression normally used for chemical plants from [6], shown in the following expression:

$$C_1 = C_0 * (P_1/P_o) \wedge {}^{0.6} \tag{2}$$

where C_0 is the cost of the small-scale plant and C_1 the cost of the full-scale plant. Normally, the exponent is 0.6 as indicated; in our case, since there are some terms that do not depend directly upon the scale factor, we adopt the exponent 0.7 to remain in a conservative hypothesis.

Doing so, we can see that the presumed cost for a big system, composed by a large storage tank and five SGs inserted in it, with a ratio P1/Po = 10 as in our case (125 MW_{th} / 12.5 MW_{th}), is

$$C_1 = 3{,}404{,}000.00 * 10 \wedge {}^{0.7} = 17{,}060{,}000.00\ € \tag{3}$$

to be compared to the cost for an ARCHIMEDE plant type of the same power (125 MW_{th}):

$$C_2 = 7{,}005{,}000.00 * 10 \wedge {}^{0.6} = 27{,}887{,}000.00\ €\ , \tag{4}$$

with a saving of about 39% for the proposed innovative TES/SG full-scale system.

Finally, it has to be considered that the TES and the external SG for an usual indirect system CSP plant of the aforesaid power, operating with temperature up to 400°C, exhibit a total cost of about 100,000,000.00 €.

4. A possible application

The OPTS Project is based on a study carried out in the past years by ENEA that had the goal to develop a configuration of thermodynamic solar plants (Chain TR.E.BIO.S.) having as their primary energy source the high temperature solar (Concentrated Solar Power), using a TES/SG system as the above described, and with the following features: - cogenerative; - medium/small size (1 to 25 MW_{th}); - distributed on the territory; - multi fuel (preferably from renewable sources); - for basic service (energy production 24/24h) through use of a backup boiler; - simplified and remote management. In this frame, a good cooperation has been established with the CESTA (Cyber Enterprise Thermodynamics Application) Project. CESTA is an advanced platform to manage heterogeneous and distributed simulation environment, cooperative-works and communications. The CESTA objectives have been finalised to improve advanced ICT technologies applied to the Concentrated Solar Power plants. The aim of the CESTA project is to promote the exploitation of concentrated solar energy through small and middle scale facilities, suitable to fulfil local requirements of power and heat, and easily to back-up with the renewable fuels locally already available or possible to be expressly produced. The implementation of the project will allow to test the CSP technology in a very advantageous location, for instance in terms of solar radiation rate, for the diffusion of this technology in other countries. Besides, it will represent the start-up for a development of specialized local industries.

The Cyber Enterprise will be tested in relation to the following systems of the CSP plant: - the control console and its visual interface; - the TES system with the integrated SG; - wifi IP video camera; - CSP start-up procedures. Finally, an innovative video-communication environment and a web-based document management system are designed both to manage cooperative works and to organize e-leaning activities using ENEA MATRIX platform.

5. Conclusions

Some preliminary experimental tests already performed at the ENEA PCS Facility have confirmed the technical feasibility of the proposed concept: an innovative system for thermal energy storage, based on a single-tank configuration with molten salts as heat storage medium (kept at a maximum temperature of 550ºC and a minimum temperature of 290°C), stratified in temperature and with an integrated steam generator for the direct production of superheated steam. These preliminary results give confidence for further in-depth studies of a system based on the above-mentioned features.

The proposal of this new concept of high temperature integrated TES/SG system has the aim of obtaining a system characterized by: - efficient performance; - simple implementation; - compactness: - modularity; - contained costs. These attributes, of fundamental importance for the integration of the TES systems utilizing molten salts in co-generative plants of small/medium size for electricity production, heat/cold production and/or for other industrial uses, should be confirmed by the experimental tests in progress and not yet concluded. The smaller volume of the storage medium respect to the two-tanks solution and the possibility to eliminate the molten salts piping for the integrated steam generator allow this system to be suitable also for large-scale CSP plants of trough or tower type.

The operating characteristics of the proposed system will be determined: - in small scale, with appropriate experimental tests on the PCS Facility, studying the behaviour of the integrated TES/SG both in the steady state operating phase and during thermal discharge/charge phases of the tank; - -in full scale, with the experimental tests foreseen in the ongoing OPTS Project, in the frame of the European 7th FP, where also the actual cost reduction c of the proposed system and its possible advantages/disadvantages in terms of operation and maintenance will be investigated.

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