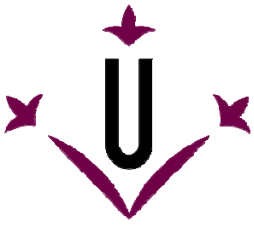

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Effects of sodium nitrate concentration on thermophysical properties of solar salts and on the thermal energy storage cost

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Abstract

Thermal energy storage (TES) systems are key components of concentrating solar power plants in order to offer energy dispatchability to adapt the electricity power production to the curve demand. Nitrate molten salts are the storage media used today in concentrated solar power plants. They are also used as heat transfer fluid (HTF) in the molten salt tower (MST) technology. Traditional MST plants work in the temperature range of 240-565°C using the so-called *solar salt*, a mixture of 60-40wt.% of $NaNO_3$ and KNO_3. This study wants to optimize the thermal energy storage cost of the solar concentration technology by analysing different mixtures of solar salts, using different percentages of $NaNO_3$ and KNO_3 in the mixture. The new mixtures seek a reduction in the cost of the storage material while optimizing its physical and chemical properties. The study shows how an increase in the proportion of sodium nitrate for a new binary solar salt to 78-22wt.%, produces an increase in the heat capacity of the mixture by reducing the necessary inventory of salts in the system. However, the new salt presents an increase in the melting point, going from 240ºC to 279ºC, which makes the operation of the system difficult. The impact on the cost of this optimization in the performance of a commercial plant was analysed. The plant chosen to evaluate the impact is a tower technology plant with 85 MWe power and 13 hours of storage. The study shows a LCOE reduction of up to 0.6% for the new mixture with higher sodium nitrate.

Keywords: molten salts; thermal energy storage (TES); Levelized Cost of Energy (LCOE)

1. Introduction

The competitive advantage of concentrated solar plants (CSP) is the capability of overcoming the natural intermittencies of the sun with thermal energy storage (TES) to produce electricity continuously beyond daylight hours [1]. Current CSP power plants use nitrate molten salts as their storage media and, depending of the technology, also as their heat transfer fluid (HTF) in molten salt tower (MST) designs. Traditional nitrate MST power plants work in the 240-565ºC temperature range using the so-called *solar salt*, a 60-40wt.% mixture of $NaNO_3$ and KNO_3.

It is well known that the range of operation temperature is not the only criterion to evaluate TES and HTF medium [2]. Thermal physical properties are also important, such as viscosity, density, specific heat capacity, and thermal diffusivity, because they are the basic and essential engineering data. These thermal properties of solar salt 60:40 are well described in several papers [2–6]. Currently many research groups are working on new mixtures that increase the thermal stability of the salts, in order to enhance the efficiency of the power cycle [7]. There are also several groups working on the search for new mixtures that have a lower melting temperature to save operating costs [2,8]. However, the impact of differing concentrations of $NaNO_3$ and KNO_3 may optimize the thermal properties from the used data.

To investigate the effects of different mixture of nitrate salts on its thermal properties, seven mixtures of $NaNO_3$/KNO_3 were selected varying the content of $NaNO_3$. This research examines the behaviour of these different molten nitrate mixtures, with the goal of improving the solar salt used currently as an energy storage fluid in CSP plants. These mixtures, which contain different weight percentages of $NaNO_3$ and KNO_3, could exhibit better physical and chemical properties than the solar salt currently used.

The melting points, heat capacities and thermal stability of the mixtures were studied by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). TGA experiments provide a good first approach to understand the thermal stability of new salt mixtures. In these experiments, a small sample of the salt is heated in an open crucible at ambient pressure with overflow of the cover gas to measure the mass evolution with time and temperature. These tests are usually employed to estimate the kinetics of the thermal decomposition reactions and, from there, estimate a reliable maximum operation temperature for a given process. To determine the specific heat, tests are carried out with a DSC. These tests measure the temperature difference between a sample and a reference material (thermal, physical and chemically inert) in function of time or temperature (sample is subjected to a temperature program in a controlled atmosphere). The specific heat is the most important

property to calculate the inventory of salts necessary for the storage system. A precise measurement of this property is critical in the design of commercial plants. The methodology has been optimized in this study using a conventional DSC and a modulated DSC.

Next, the levelized cost of energy will be used to calculate the potential benefit that the use of the new higher sodium concentration salts compared with the used today *solar salt*.

2. Material and methods

2.1. Materials

All the tests of binary mixtures of $NaNO_3$ and KNO_3, were done with pure salts from SQM®. The chemical compositions of the sodium and potassium nitrate used for the experimental analysis developed are included in Table 1.

Table 1. Chemical composition of pure $NaNO_3$ and KNO_3 from SQM (weight%)

Purity/Impurities	**$NaNO_3$**	**KNO_3**
Purity (%)	99.5 min	99.6 min
Chloride (%)	0.1 max	0.1 max
Magnesium (%)	0.02 max	0.01 max
Nitrite (%)	0.02 max	0.02 max
Sulfate (%)	0.10 max	0.05 max
Carbonate (%)	0.10 max	0.02 max
Moisture (%)	0.1 max	0.1 max

2.2. Mixtures preparation

The binary mixtures studied are presented in Table 2. Before any analysis, it is important to dehydrate the samples in order to measure thermal characteristics of salts without bounded water [9]. Therefore, the samples were prepared first, heating at 300 ºC the base salts during 20 min, we poured in a mortar, crushed and kept separately in a dry box. Each mixture was done in the same way. The base salts were mixed in the corresponding weight concentration. The mixture was heated at 400ºC for 20 minutes and mixed manually with a stick. The mixture was

then poured in a mortar, crushed until a fine powder and kept in a dry box. Before each thermal measurement, the mixture was heated at 200ºC during more than 10 hours.

Table 2. Mixtures tested in the experiment campaign

Mixture number	wt.% $NaNO_3$	wt.% KNO_3
1	0	100
2	20	80
3	40	60
4	55	45
5	60	40
6	80	20
7	100	0

2.3. Analytical methods

The heat capacity (C_p) measurements were carried out with a DSC2 from Mettler Toledo. The DSC technic measures the heat capacity by heating a sample and measuring the difference between the heat flows from the sample (mixture in crucible) and a reference (empty crucible) as function of temperature. Samples are placed in a 40 µL aluminum crucible with a small hole on the tap. The heat capacity is calculated from heat flow values of three different measurements: blank (two empty crucibles), sapphire (crucible with sapphire disc and empty crucible), and sample (crucible with sample and empty crucible).

The DSC method shows imprecision due to the high level of deviation, around 10% RSD. The Relative Standard Deviation (RSD) was reduced in this study working in other parameters, such as the blank and sapphire reference, the crucible position on the sensor and the sample contact on the bottom of the crucible. The measurements of the blank, sapphire, and different mixtures (called pack) were performed in immediate succession to be sure that the measurements have the same imprecision and reference.

In order to avoid salt creeping out of the crucible, the sample crucibles were prepared with the salt crushed in a fine powder and a maximum of 10 mg of salt is placed in each crucible. Furthermore, to ensure as much as possible the same contact of the salt on the bottom of the crucible, the samples are measured only one time. Once the salt was melted inside the crucible, by surface tension, the salt goes on the walls of the crucible and the contact of the bottom of the crucible is not the same. These change of contact leads to high imprecision in C_p measurement.

Finally, crucibles were placed manually in the DSC. The authors of this paper observed that the blank placed manually in the DSC showed an error of only 5% while a blank placed with a DSC robot showed an error up to 10%. The conditions to test and measure the heat capacity of the sample were as follow. In an atmosphere of N_2 at 50 mL/min, the following ramp was programmed: isothermal ramp at 370ºC for 5 minutes, dynamic ramp at 20 K/min from 370ºC to 500ºC, and isothermal ramp at 500ºC for 3 minutes. Entire packs are measured 12 times and important mixtures as pure KNO_3, the eutectic (55wt.% $NaNO_3$), the solar salt (60wt% $NaNO_3$), and pure $NaNO_3$ were measurement more times. Table 3 shows the number of measurement for each mixture.

Table 3. Number of measurements for each mixture.

Mixture	Number of DSC measurements
1 (Pure KNO_3)	17
2	12
3	12
4 (eutectic)	19
5 (solar salt)	29
6	12
7 (pure $NaNO_3$)	18

Modulated DSC is interesting compared to conventional DSC because it does not need a blank in the methodology. The technic consists in introducing a modulation in temperature according to a sinusoidal function around a constant temperature during a certain time. In this way, the reversible C_p is calculated from the amplitude of the modulated signal of heat flow according to the following relation:

$$RevC_p = \frac{Heat\_flow\_amplitude}{Heating\_rate\_amplitude} * KC_p \qquad \text{Eq. 1}$$

where KC_p is a calibration constant, which depends on the equipment and is calculated by the mean of a reference line. In this case, sapphire is the reference line. If there is no thermal event, the reversible C_p is zero whereas when modulating the temperature, the reversible C_p corresponds to the conventional C_p. Experimental conditions were those described in the ASTM E2761-09 standard. The modulation programmed had 0.6ºC temperature amplitude and 60 s frequency around the mean temperature, 450ºC. The mean temperature was maintained for 30

minutes to allow the stabilization of the heat flow signal and be sure of the precision of the measurement.

In order to analyze the peak transition of each mixture, the heat flow was measured from 170ºC to 390ºC with a heating ramp of 20ºC/min, using the DSC described above. For each mixture, the measurement was done three times to validate the results. The latent heat and the melting temperature of the salt mixtures were calculated with the Mettler Toledo software. The latent heat was calculated by integrating the area under the heat flow curve in which the melting temperature was defined as the onset temperature. Only the solid-liquid phase transition was investigated in order to know the minimum working temperature in a CSP plant.

The stability temperature was measured by thermogravimetric analysis (TGA). The equipment is the same as a DSC but the sensor is connected to an ultra-sensible balance and allows measuring the mass change of the sample at any moment, when the sample is submitted to a temperature isothermal or dynamic ramp. In that case the interest is to measure the temperature when the sample lost 3% of its total initial mass. The thermal ramp programmed is 20ºC/min from 400ºC to 900ºC.

3. Results

3.1. Specific capacity results with conventional DSC

The mean value of each mixture was calculated in the temperature range between 380ºC and 485ºC and the mean over all the samples of the same mixture (Table 3). The mean value of C_p (with its associated error) versus the mixture composition is represented in Figure 1. It is interesting to note that the points follow a line.

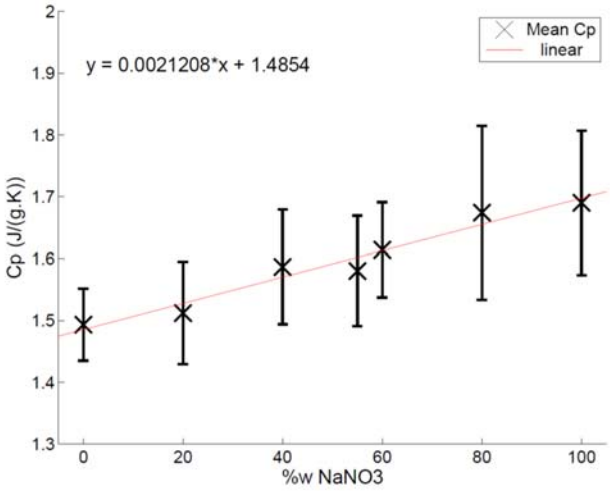


Figure 1. Heat capacity of each mixture composition with conventional DSC.

Thanks to the corrections followed in the methodology and described in the methodology section, it was possible to reach a RSD below 8.4% for all the measurement and a mean RSD of 5.8%, which is a very good precision for this equipment (Table 4).

Table 4. Results of heat capacity and RSD associated for all the binary mixtures studied, when using conventional DSC.

$NaNO_3$ (wt.%)	Cp (J/g·K)	RSD (%)
0	1.4934	3.8
20	1.5123	5.4
40	1.5867	5.8
55	1.5802	5.6
60	1.6141	4.7
80	1.6739	8.4
100	1.6900	6.9

3.2. Specific heat capacity results with modulated C_p methodology

Figure 2 presents the mean C_p value for the mixture composition. It is interesting to note that, again, the points follow a line. With this modulated technic, the linearity is confirmed and shows the same slope as conventional DSC. The modulated technic is much more precise than conventional DSC methodology, with a maximum RSD of 2.3% (Table 5).

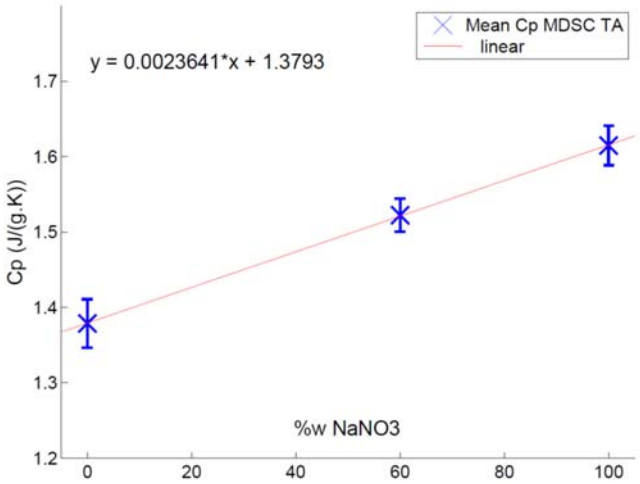


Figure 2. Heat capacity versus mixture composition with modulated DSC.

Table 5. Results of heat capacity values and RSD associated when using modulated DSC.

$NaNO_3$ (wt.%)	Cp (J/g·K)	RSD (%)
0	1.3788	2.3
60	1.5224	1.4
100	1.6149	1.6

Both methods to determine the heat capacity present similar trends that follow the mixing low. According to these results, a salt with higher concentration of sodium nitrate will have higher heat capacity. This C_p increase will have a positive impact in the solar plant cost, reducing the storage size and the total salt mass flow required.

3.3. Melting point and heat of fusion results

Table 6 shows the results of the melting point and heat of fusion from the DSC analysis. Both onset and endset values are given, since both are used to give the melting temperature of storage materials. It can be seen that the melting temperature is maximum for the pure materials (being higher for $NaNO_3$) and it decreases until a minimum for the mixture known as solar salt (60wt.% $NaNO_3$ and 40wt.% KNO_3). Figure 3 shows the results of melting temperature with those from Janz et al. [10]. On the other hand, the melting enthalpy of the increases when increasing the amount of KNO_3 and, as expected, follows the law of mixtures.

Table 6. Results of melting temperature and heat of fusion for all mixtures

$NaNO_3$ (wt.%)	Onset (ºC)	RSD (%)	Endset (ºC)	RSD (%)	Enthalpy (J/g)	RSD (%)
0	332.93	0.07	341.63	0.16	105.96	1.15
20	233.20	0.04	265.59	0.44	102.76	0.96
40	222.04	0.11	231.82	0.30	112.31	0.83
55	222.54	0.08	235.00	0.28	121.65	0.75
60	221.97	0.16	238.16	0.17	123.11	1.04
80	243.25	0.35	283.26	0.29	195.73	0.72
100	304.63	0.05	316.47	0.34	191.33	2.16

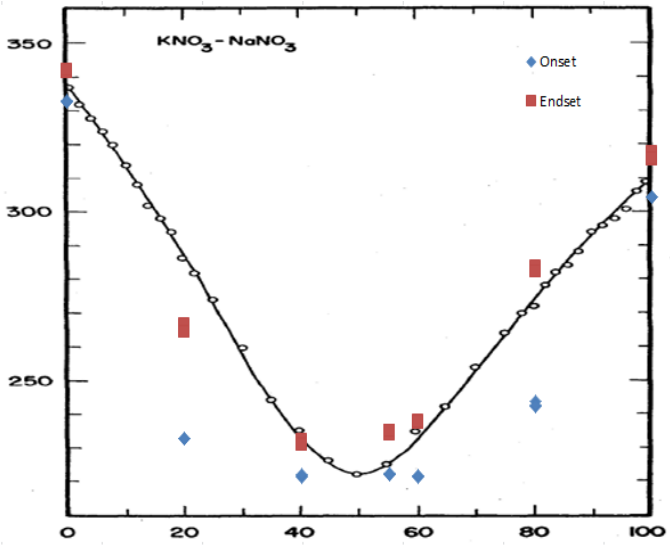


Figure 3. Results of the melting temperature if the studied mixtures compared to Janz et al. [10].

The measured latent heat for $NaNO_3$ was 191.3 J/g, which is higher than the existing data [11]. Salt mixtures with sodium concentration higher than that of *solar salt* (60:40) present higher melting point. In a CSP plant, the use of a storage material with higher melting point would involve a potential increment of operational problem due to salt freezing. Table 6 shows that those mixtures also have a higher melting enthalpy, which would mean the need of additional energy to melt the salt mixture when filling the storage tanks during the start-up phase.

3.4. Thermal degradation

Figure 4 presents the % mass loss for each temperature. All seven mixtures show similar thermal degradation profile. On the other hand, the stability temperature is defined as the temperature when the sample has lost 3% of its initial total mass. The stability temperature for each mixture is shown in Figure 5. These measurements show that the stability temperature is constant for all the mixtures, with a mean value of 646ºC and a RSD of 1.7%.

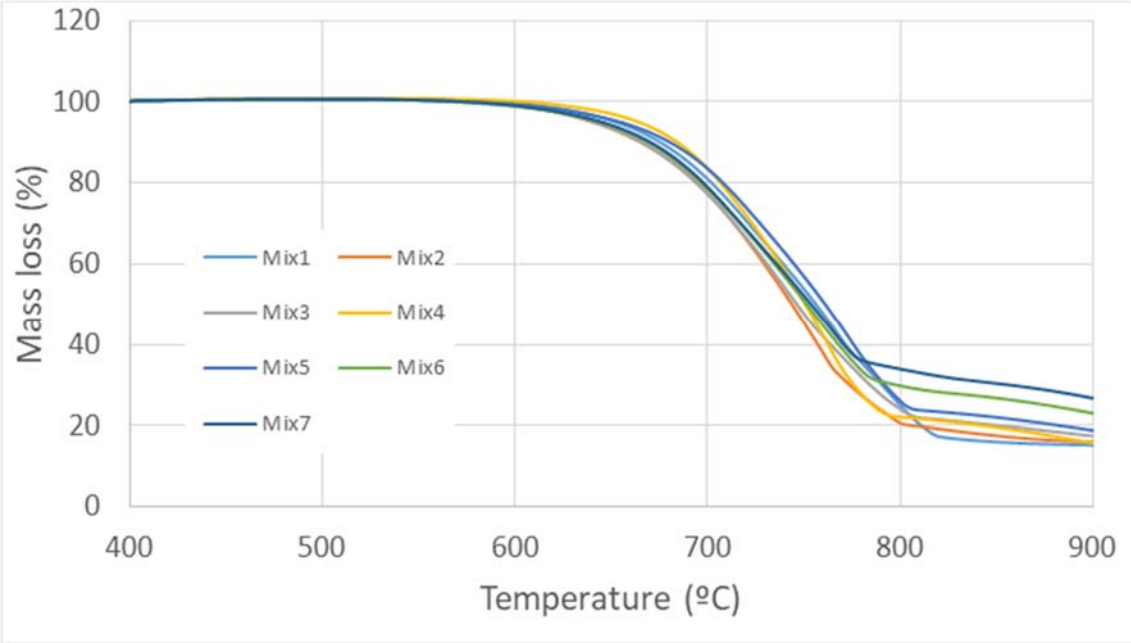


Figure 4. Mass loss of the studied mixtures.

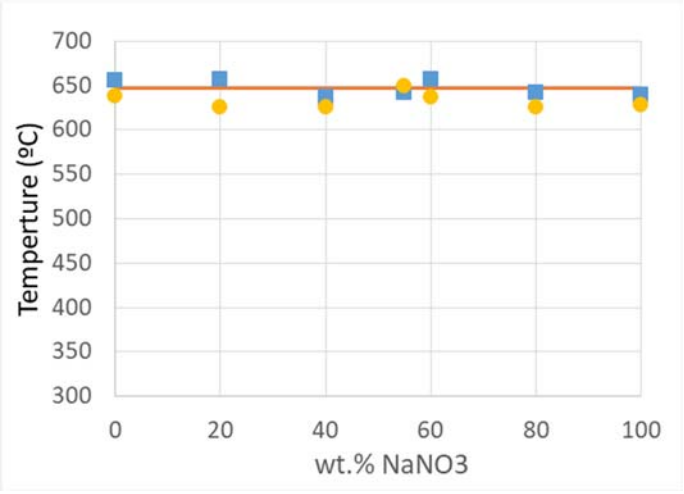


Figure 5. Stability temperature of the studied mixtures.

Thermal degradation is an important parameter to evaluate for the validation of a new salt for thermal energy storage in CSP plants. Excessive level of degradation can involve the apparition of new products that could modify the thermal properties of the storage material or even increase the aggressiveness of the salt in terms of corrosion. The TGA analysis carried out in this paper does not show any dependence between the thermal degradation and the sodium nitrate concentration variation.

4. Economic analysis

4.1. Definition

Molten salt is the most widespread heat transfer fluid for thermal energy storage in CSP commercial applications due to its good thermal properties and reasonable cost. Nowadays, molten salts provide a thermal storage solution for the two most mature technologies available on the market (e.g. parabolic trough and tower) and could be used as direct and indirect storage depending of the selected plant philosophy. Both, trough and tower technologies, use double tank system as thermal storage configurations [1].

In general, molten salt storage systems offer the possibility to supply electrical production at constant conditions thanks to maintain the storage material in different tanks when it is charged or discharged. It also becomes an interesting option as storage material because it has high energy density per specific volume and very high thermal inertia due to its high heat capacity and low thermal conductivity. In the state-of-the-art, there are several publications that show the thermal properties of molten salts, for example *Bauer et al.* [12] makes a good comparison of the different correlations. The optimization of the thermal properties of molten salt allows like the design of storage systems with minimum thermal losses that increases global efficiency of the plant or with lower inventory due to the highest heat capacity.

As shown in the previous sections, an increase in the proportion of sodium nitrate in the binary solar salt 60/40 produces an increase in the main properties as heat capacity, melting point and melting enthalpy. Now, the economic impact of the use of salts with higher sodium concentration salts in a commercial plant is studied. The plant chosen to evaluate this impact is a tower technology plant with 85 MWe power and 13 hours of storage, that uses solar salt as HTF and storage medium. A solar tower plant consists of a large field of heliostats, a heat transfer fluid/steam generation system, and a Rankine steam turbine/generator cycle [13]. The direct double tank molten salt storage system is used in the thermal energy storage system [1].

The economic study is focused on the storage system since it is the component that would have the most relevant cost impact. It is taken as an indicator.

The heat capacity and density increase are considered as the two most important parameters because it allows an exponential decrease in the salt flow required and consequently an important reduction in the pump consumption. On the other hand, these two parameters enhancement will also involve a direct reduction in storage systems, specifically, the heat capacity in the molten salt inventory required and the density in the size of the overall storage system. Furthermore, due to the manufacturing process, potassium nitrate is usually more expensive than sodium nitrate and thus, salts inventory with higher sodium nitrates will be less expensive than the one used today.

On the other hand, higher melting point, viscosity and heat of fusion will impact negatively in the plant in different ways. The higher melting point will involve a higher risk of block formation due to salt freezing, therefore, the electric heater systems installed in the plant to prevent this problem will need to be re-designed. Furthermore, a higher viscosity, more significant at lower temperature, will increase the pressure drop associated in the cold part of the facility and, consequently, the pump power required. Finally, salts with higher melting enthalpy will also involve higher energy consumption during the melting process in the plant start-up period.

Table 7 shows the variation of these main parameters with concentration of sodium nitrate concentration. The physical properties ratios for heat capacity, melting point and melting enthalpy were obtained from the experimental results showed in the previous sections. The correlation for viscosity and density were calculated from data published in Janz et al. [10].

Table 7. Correlation of the physical properties considered in the economic evaluation.

Property	Correlation	Regression coefficient
Heat capacity (kJ/kg·K))	$y = 0.0021208 \cdot x + 1.4854$	$R^2 = 0.9555$
Melting point (ºC)	$y = -0.0003 \cdot x^3 + 0.086 \cdot x^2 - 5.7096 \cdot x + 343.46$	$R^2 = 0.9907$
Heat of fusion (kJ/kg)	$y = 0.03288 \cdot x + 101.65$	$R^2 = 0.8061$
Viscosity (Pa·s)	$y = -0.8069 \cdot x^2 + 0.0826 \cdot x + 3.3926$	$R^2 = 1.0000$
Density (kg/m^3)	$y = 0.0218 \cdot x + 1.857$	$R^2 = 0.9945$

x= sodium nitrate wt.% in the binary mixture

The levelized cost of energy (LCOE) is the price at which electricity generated from a specific source breaks even over the lifetime of the project [14], and can be formulated with:

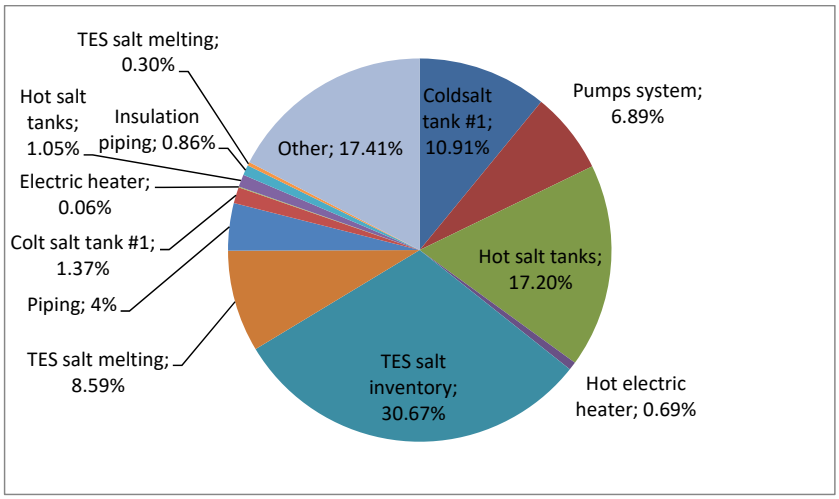
$$LCOE = \frac{f \cdot C_{inv} + C_{O\&M}}{E_{net}} \qquad \text{Eq. 2}$$

where C_{inv} is the first investment cost, $C_{O\&M}$ the annual operational and maintenance cost and f indicates the time dependent interest rate. According to Kearney et al. [5], an interest ratio of 0.104 is a representative value for this type of plants.

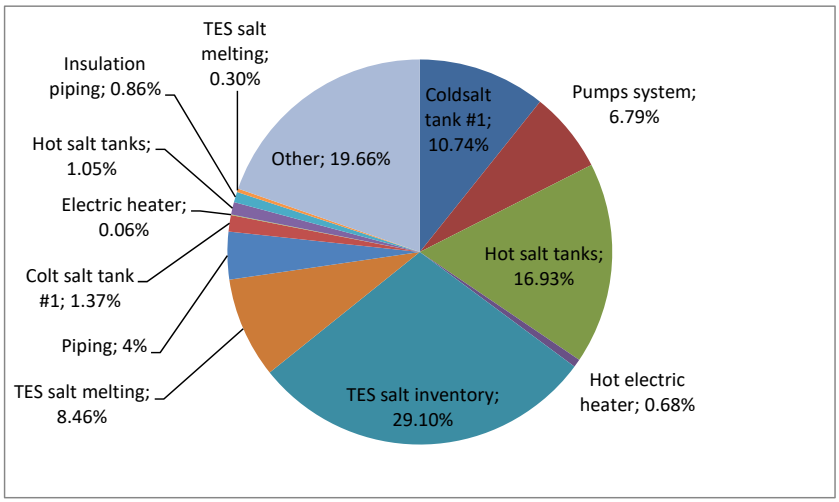
4.2. Variation in the investment cost (C_{inv})

As it has been mentioned, higher heat capacity and density of the new salts will allow the reduction of the storage system cost. According to an internal model developed at Abengoa, in a 85 MWe tower plant with 13 hours of storage, the total storage cost represents around 11.03% of the total cost, corresponding 4.05% to the salt inventory cost and 6.98% to the rest of the plant; hot and cold tanks, pumps, foundations, structures, insolation, piping associated, salt melting systems and assembly. Similar values are published by Kolb et al. [15] and by IRENA [16].

The investment cost will be also reduced due to the lower cost of the higher sodium concentration salts in comparison with the *solar salt* (60/40 mixture). In this paper it assumed that the supply cost of potassium nitrate is 65% higher than the sodium nitrate cost, according to internal data from salt suppliers of Abengoa. The distribution of cost component and the variation with the original case is shown in the Figure 6.



(a)



(b)

Figure 6. Comparison of TES cost for (a) *solar salt* and (b) new mixture molten salt

A reduction cost comparison has been developed in Figure 7. The study releases a molten salt cost reduction up to 5%, and a TES cost reduction up to 2.5%.

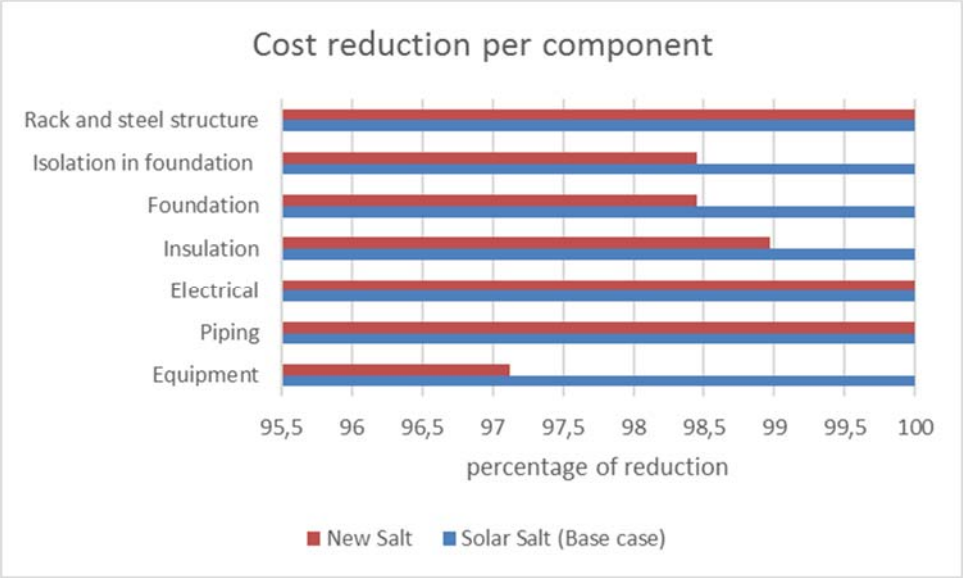


Figure 7 Comparison of cost reduction per TES component

The cost required to melt the total salt inventory in the base case represents around 0.007% of the total investment cost, assuming a natural gas cost of 0.59$/MWh, initial salt temperature of 25ºC and final melted salt temperature of 360ºC. According to the experimental results, higher sodium concentration salts will require more energy to be melted, due to the higher concentration of sodium nitrate.

Considering the premises exposed above, the investment cost (C_{inv1}) with the new salts compared with the investment cost of the case base (C_{inv0}) will be:

$$\frac{C_{inv1}}{C_{inv0}} = 1 + (4.05\%)\left(\frac{C_{p0}}{C_{p1}} - 1\right)\left(\frac{P_{r0}}{Pr_1}\right) + (6.98\%)\left(\frac{C_{p0}}{C_{p1}}\frac{\rho_{p0}}{\rho_{p1}} - 1\right) + (0.007\%)\left(\frac{C_{p0}}{C_{p1}}\frac{H_{f0}}{H_{f1}} - 1\right) \quad \text{Eq. 3}$$

where, $\frac{C_{p0}}{C_{p1}}$ is the heat capacity ratio, $\frac{P_{r0}}{P_{r1}}$ the price ratio, $\frac{\rho_{p0}}{\rho_{p1}}$ the density ratio, and $\frac{H_{f0}}{H_{f1}}$ the heat of fusion ratio.

4.3. Variation in the Net energy produced (Enet)

As mentioned previously, regarding the energy production, the new salts only will impact in the parasitic consumption associated to the pumping system. For this type of plants, the total parasitic consumption achieves between the 5% and 10% of the gross electrical production, most of this energy is associated to the molten salt pumping system [17,18]. For the plant selected, with 85 MWe and 13 hours of storage, internal analysis of Abengoa releases pumping

consumption close to 3.6% of the net annual production. Considering this value, the net energy produced of a potential plant with higher sodium concentration salt compared with the case base will be:

$$\frac{C_{inv1}}{C_{inv0}} = (3.6\%)\frac{P_{p1}}{P_{p0}} \qquad \text{Eq. 4}$$

where, P_{p1} and P_{p0} are the salt pumping consumption of the new plant and the case base respectively. The power consumption of the pumpP_p, is formulated as:

$$P_p = \frac{Q*H}{\tau} = Q^3 f \frac{8\,L}{D^5 g\,\pi^2} \qquad \text{Eq. 5}$$

where, Q is the volumetric salt flow, L and D the length and inlet diameter of the pipe, g the gravity, and f the friction factor that can be assumed for turbulent regimen by the next expression:

$$f = \frac{0.25}{log\left(\frac{k}{3.7D}+\frac{5.74}{Re^{0.9}}\right)^2} \qquad \text{Eq. 6}$$

where, k is the absolute roughness of the piping, which for carbon steel pipe is considered 0.045 mm [19] and Re the Reynold number, defined by:

$$Re = \frac{\rho*v*D}{\mu} \qquad \text{Eq. 7}$$

where v is the velocity trough the piping, and μ and ρ are the viscosity and density of the salt at the operation temperature, respectively.

According to Kearney [20], the volumetric flow of molten salt pumped can be determined in a solar plant with:

$$Q = \frac{Power}{\rho*C_p*\Delta T} \qquad \text{Eq. 8}$$

where *Power* is the thermal power absorbed by the salt in the solar receiver, ΔT, the increment of temperature in the solar receiver and C_p the average heat capacity between the inlet and outlet of the receiver. Considering that the plants objective of this study have the same thermal power,

same increment of temperature and similar length of piping for each diameter, Eq. 4 can be reformulated as:

$$\frac{C_{inv1}}{C_{inv0}} = (3.6\%)\frac{log\left(\frac{k}{3.7D}+\frac{5.74}{Re_0^{0.9}}\right)^2}{log\left(\frac{k}{3.7D}+\frac{5.74}{Re_1^{0.9}}\right)^2}\left(\frac{\rho_0}{\rho_1}\frac{cp_0}{cp_1}\right)^3 \qquad \text{Eq. 9}$$

with $$Re_1 = Re_0\left(\frac{\mu_0}{\mu_1}\frac{cp_0}{cp_1}\right) \qquad \text{Eq. 10}$$

4.4. LCOE

LCOE enhancement was calculated considering Eq. 3 and Eq. 9. An annual operational and maintenance cost of 17 M$ [21] and a representative pipe diameter of 22 inches were considered.

Figure 8 shows the LCOE enhancement (in %) considering different salts with sodium nitrate concentration between 60% (base case) and 78%. The figure also shows the melting points corresponding to each salt, result of the measurements carried out.

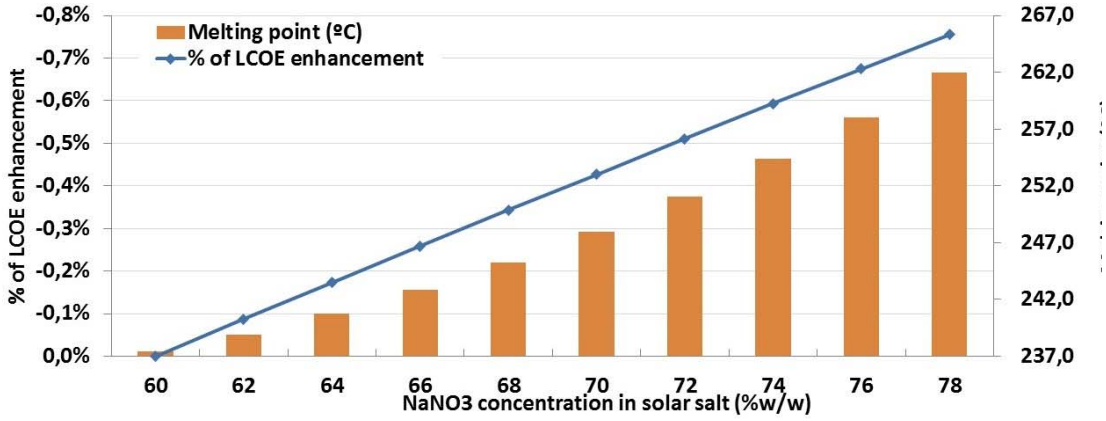


Figure 8. LCOE enhancement and melting point versus the sodium nitrate % in a binary nitrate salt mixture.

The analysis releases a slight enhancement of the LCOE due mainly to the cost reduction due to pumping consumption and the lower storage size required. The negative point is the higher melting point of these new salts that will entail higher risk of block formation due to salt freezing. To avoid that, the set point of the current electric heater installed in the plant should be re-designed. The cost involved to this effect was not included in the present paper and could be experimentally analyzed in future studies.

For future development, the dynamic on the molten salt tank and parasitic consumptions will be analyzed. A second study is under development where a new performance model is evaluated.

5. Conclusions

This paper describes the impact of the use of salts with higher sodium concentration salts in a commercial plant performance. Experimental analysis of innovative mixtures of $NaNO_3$ and KNO_3 has been carried out to determine the effect of a higher sodium nitrate concentration in the main properties required for heat transfer fluids and storage medium in CPS plants. The plant chosen to evaluate the impact is a tower technology plant with 85 MWe of power and 13 hours of storage.

Heat capacity, heat of fusion, melting point and thermo-gravimetric analysis of different composition of sodium nitrate and potassium nitrate mixtures were carried out.

Two different methods were used to determine the heat capacity, conventional DSC, that use a reference to determine the C_p and a modulated DSC, that does not need a blank line. Both methods present similar trends that follow the mixing low. According to these results, a salt with higher concentration of sodium nitrate will have higher heat capacity. This increase in C_p will have a positive impact in the solar plant cost, reducing the storage size and the total salt mass flow required for the storage.

Melting enthalpy and melting temperature of the different mixtures considered were also determined and the results confirmed data from the literature. The main result is that salts with sodium concentration higher than the *solar salt* (60:40) will have higher a melting point. In CSP plant, the use of salt with higher melting point will involve a potential increment of operational problem due to salt freezing. This type of salts also presents a higher melting enthalpy and the main consequence, compared to the *solar salt*, is the additional energy required to melt the salt during the tank filling, in the start-up phase.

The stability temperature of seven different mixtures were measured with TGA, the results do not show a significant variation of thermal degradation for salts with different concentration of sodium nitrate.

These experimental data and other obtained from literature were used to determine the increase in LCOE of a tower type plant using salt with higher concentration in sodium nitrate salts versus the current plant using the *solar salt*. The study includes the benefit entailed to the higher heat

capacity and density of the new salts, as well as the lower price. On the other hand, also the negative impact of the higher viscosity and melting temperature were considered. The main handicap in the use of higher concentration sodium salt is the higher melting point and consequently, the higher risk of block formation due to salt freezing.

This preliminary study releases a molten salt cost reduction up to 5%, a TES cost reduction up to 2.5% and a LCOE reduction up to 0.6% for salts with 78wt.% sodium nitrate, with a melting point of 279ºC. In the new studies, the optimal salt concentration will result from the balance analysis between the lower LCOE and higher risk associated to a greater melting point.

These preliminary results encourage continuing with the validation of the new mixtures, developing a new performance model where dynamic effects and parasitic consumption are analyzed in more detail.

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