THE VALUE OF SOLAR SALT SPECIFIC HEAT ENHANCEMENT IN CONCENTRATED SOLAR THERMAL PLANTS

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Abstract— It has been recently reported that nanoparticle dispersions in molten salt mixtures can significantly enhance the specific heat capacity of the salt mixtures. Molten salt eutectics can be used as heat transfer fluids (HTF) and/or thermal energy storage (TES) in a concentrated solar thermal (CST) plant. For either purpose, enhancing their specific heat capacity can theoretically improve CST system performance. However, to date no literature has determined how advantageous an enhancement of specific heat might be in a CST system or its subcomponents. In addition, since there is a cost associated with this enhancement, it is imperative to investigate the *net* economic limitations and benefits. To address these issues, this paper analyses how HTF specific enhancements in the range of 5-200% influence the CST-tower plant components. The results imply that increasing the HTF specific heat can reduce the storage volume by up to 80%. It was also found that the solar field mass flow rate and parasitic loads can also be decreased by up to 90%, while the net power output of CST-tower plant can be increased by up to 3%. Of course, nanoparticles (or other) costly additives are required to achieve these enhancements. Thus, this study poses the question of what premium could be paid (above the base solar salt cost of 1USD/kg) and still obtain an economic advantage. It was found that if specific heat is enhanced by 30%, a 50% premium on the pure salt is justified. If, however, a specific heat enhancement of 120% is possible (the maximum reported in the literature); a 300% premium yields an economic break-even point. Ultimately, this study reveals that if i) long-term, stable enhancements of 30-120% are indeed possible via the addition of ~1% of nanoparticles and ii) if nanoparticles (e.g. < 30 nm silica spheres) can be mass produced at < 50-200 USD/kg, they will have a significant positive return on investment in CST applications.

Keywords— Nanoparticle, Specific Heat Enhancement, Concentrated Solar Thermal.

I. INTRODUCTION

Concentrated solar thermal (CST) power has become a key player in helping the energy sector reduce its carbon footprint. In comparison to photovoltaic and wind, the thermal storage aspect of CST enables a relatively good match with demand. However, achieving more efficient and cheaper CST technologies remains a challenge.

At present, tower systems have a number of potential advantages that they could soon make them the preferred CST technology [1]. As tower systems operate at higher temperatures than parabolic troughs, they can achieve higher efficiency and use higher quality thermal storage systems. By integrating a CST-tower power plant with thermal energy storage (TES), excess solar energy can be stored during periods of high insolation, and then discharged when it provides the most value to the grid/plant operator. The literature has shown that a well-designed TES system can make power plants more cost effective – 2.5% higher net present value (NPV) and 10% reduction in the levelized cost of electricity have been reported [2, 3].

The most mature large-scale TES technology is the two-tank system, using nitrate-based molten salts [3, 4]. In spite of the high reliability of this kind of sensible heat storage (SHS) system, it requires relatively high volume of salt, due to low specific heat values of molten salts. This results in high capital cost and the salt itself is the most expensive component of TES (typically half of the storage system cost [5]). The two tanks account for around a quarter of the cost and pumps and plumbing represent the remainder. Improving TES materials and designs has become a hot topic for research and development, since it provides a pathway for significant CST plant cost reduction. In fact, it has been estimated that cheaper materials and improved operation alone could reduce the TES system's cost by between 38-69% [6]. As the salt itself represents nearly half of the cost of TES, another feasible avenue of cost shaving is to reduce the salt volume required by enhancing the salt's specific heat.

It has been shown in several studies that specific heat can enhanced by dispersing nanoparticles into molten salts [6]. Although it is in early stages of research (and there is still some controversy), it has been shown that the addition of 1-2 weight % of nanoparticles can yield a specific heat increase of 15% to 120% [8]. To date, though, most researchers focused on the materials and thermal properties aspects of this issue, rather than what it could mean for the actual application. Questions like: "How much enhancement is needed?" and "How does a given specific heat enhancement help the technical and economic viability of the CST plant?" have not been explored. As a result, the aim of this study is to evaluate the impact of specific heat enhancements on molten salts from a systems perspective. This is evaluated through a detailed, validated thermodynamic model that can assess various specific heat enhancement values and economic inputs.

II. CST-TOWER PLANT DESCRIPTION

A schematic illustration of a CST-tower plant configuration with an integrated storage unit is presented in Fig. 1. As can be seen, the three major sub-components of CST-tower plants are the solar receiver, the storage unit, and the power block (the Rankine cycle). The HTF, molten salt, absorbs solar energy in the receiver, and then it can either exchange heat in the power block heat exchangers or be stored in storage unit for later use. To analyse how the specific heat of the molten salt affects these three main subcomponents, a model has been developed to simulate all three major components of the CST plant. This model has been developed by integration of previous validated models of each subcomponent [9, 10]. At the design operational point, the HTF temperature from the solar field is 565 ˚C, and it will exit the power block with a temperature of 286 ˚C. These two temperatures drive the design of any TES unit in CST-tower plants. These design constrains are obtained from available data for the 20 MW_e Gemasolar power plant [11]. The properties of pure solar salt (a eutectic consisting of 60% NaNO3 : 40% KNO3) are shown in Table 1.

Based on the design operational point data of Gemasoalr power plant and solar salt thermophysical properties, the model was validated with the Gemasolar power plant reported operational output data. [11]. The simulation results of 20 MW_e CST-tower plant are shown in Table 2. It should be noted that the solar multiple considered in simulations is 2.5, based on Gemasolar power plant, so the solar field flowrate at design point is 2.5 times higher than the required mass flowrate in power block heat exchangers, 350 kg/s versus 142 kg/s. Also the height of the tower is considered to be 142 m, as the Gemasolar plant. While the gross power output at operational capacity is 20 MW_e, the parasitic load of solar field pump (0.75 MW) results in a net power output of 19.25 MW_e at the design point.

As molten salt does not circulate in the solar field and the power block, since the HTF in the power block is different, therefore, it is evident that increasing the specific heat of solar field HTF (solar salt) does not influence the HTF in the Rankine cycle (water/steam). Hence, for this reason the parasitic load in power block is neglected in this study. In the next section, an analysis will be performed to find how specific heat enhancement can change the results reported in Table 2.

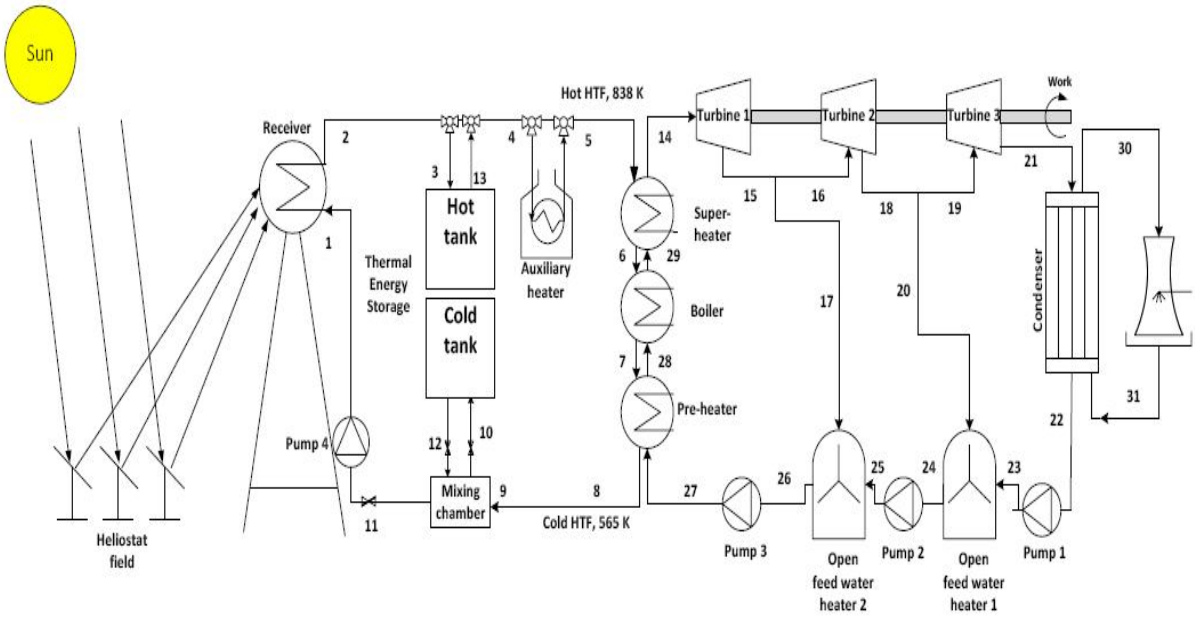


Fig. 1. Major subcomponents of the CST-tower plant: Solar receiver, two-tank thermal energy storage, and the Rankine cycle.

Table 1. Thermophysical properties of solar salt – Data from [12]

		HTF thermal properties
Name	Unit	Solar Salt (40%KNO_3: 60% $NaNO_3$)
Dynamic viscosity	kg/m s	0.00326
Density	kg/m^3	1820
Specific heat capacity	J/kg.K	1553
Thermal conductivity	W/m.K	0.52
Decomposition temperature	˚C	600

Table 2. Baseline results of 20MWe CST-tower model at the design point

Parameter	Unit	Value
Steam mass flow rate	$kg.s^{-1}$	23.7
Rankine cycle efficiency	-	0.33
Gross power output	MW_e	20
Required HTF for design point operation	$kg.s^{-1}$	142
Heliostat field area	m^2	296,000
Number of receiver tubes	-	33
Receiver surface area	m^2	412
Receiver aperture area	m^2	330
Receiver surface temperature	K	771
Receiver thermal output	MW	142
Receiver efficiency	-	0.89
Solar field mass flow rate	$kg.s^{-1}$	343

III. THE PHYSICAL INFLUENCE OF SOLAR SALT SPECIFIC HEAT ENHANCEMENT

In the previous section, the CST-tower simulation results were validated with the Gemasolar power plant operational data reported in the literature. Hence, the influence of specific heat enhancement of solar salt can now be investigated on the TES system and the CST-tower power plant. The solar salt specific heat enhancement affects the receiver and the storage unit directly, but through these has an indirect effect on the whole plant. The Gemasolar 20 MW_e power plant requires 915 MW-h heat storage to be able to cover 15 hours of operation. As the specific heat of solar salt is enhanced, less volume of salt is required to store the same amount of energ.y. Therefore, Eq. (1) to Eq. (3) were used to size the storage unit.

$$\dot{Q}_{HTF} = \dot{m}_{HTF} C_{p,HTF} (T_{HTF,HOT} - T_{HTF,COLD}) \quad (1)$$

$$Q_{HTF,total} = \int_0^t \dot{Q}_{HTF}\, dt \quad (2)$$

$$V_{SHS} = \frac{Q_{HTF,total}}{\rho_l c_{pl} (T_{HTF,hot} - T_{HTF,cold})} \quad (3)$$

The volume of storage medium can be calculated with regard to the mas flow rate required for powering the Rankine cycle at design point (142 kg/s) and the hours of storage (e.g. t=15 hours in Gemasolar plant). According to Eq. (3), it is evident that when the specific heat is enhanced, for storing a specific amount of thermal energy, less volume would be required. Furthermore, Eq. (1) shows the transient amount of delivered energy. Hence, for extracting a specific amount of thermal energy from the storage unit, the system with higher specific heat requires lower mass flow rates. Lower mass flowrates in solar field have two advantages. On one hand, it reduces the pumping power required in the solar field up to the receiver as shown by Eq. (4)-the pump efficiency is assumed 0.6. On the other hand, consuming less amount of pumping energy means less parasitic loads compared to a plant with In order to investigate the benefits of specific heat enhancement, a range of +5% to +200% was considered in this study. The effect of specific heat enhancement on storage volume is depicted in Fig. 2. As it can be seen, depending on the percentage of specific heat enhancement, the storage volume can decrease up to 80% for 200% enhancements in the specific heat. Since (as mentioned before) ~50% of TES cost is salt cost, this volumetric savings can result in huge cost reduction of TES relative to pure salts, if it can be obtain cheaply. The effect of this enhancement on the system is explored in the next section.

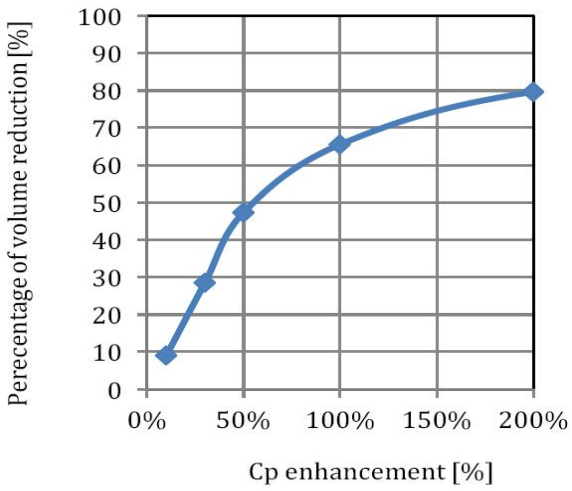


Fig. 2. The effect of specific heat enhancement on storage medium volume to store 915 MW-h heat

In order to calculate the required mass flowrate to reach the desired temperature at outlet of the receiver as a function of direct normal irradiation (DNI), the solar field model was deployed. Similar to what is expected in Eq. (1), the solar field mass flowrate decreased up to 90% as shown in Fig. 3. The percentage of reduction in parasitic loads is calculated based on Eq. (4) and shown in Fig. 3.

The circulating mass flow rate in receiver is decreased by increasing the HTF specific heat. As mentioned before, since the HTF in the power block is different, the gross power output by the power block did not change when performing the CST-tower simulations with enhanced solar salt specific heat. However, the net power output of the plant with

enhanced specific heat is higher than that of with pure salt due to the reduction in parasitic pumping loads. Hence, Fig. 4 implies that the net power output can increase up to 3%, corresponding to specific heat enhancement of 200%. It is worth noting that increase in the viscosity of solar salt due to addition of nanoparticles was not considered in this study. However, as only 1wt.% of nanoparticle is reported in the literature to be added to solar salt, increase in viscosity could be negligible. Thus, the 3% increase in net power output could be neglected if increase in viscosity of salt is considered.

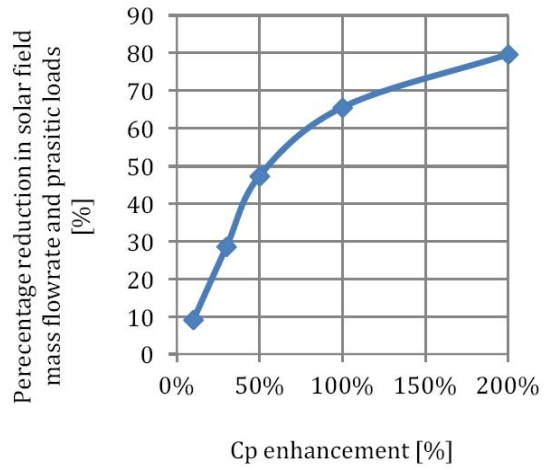


Fig. 3. The effect of specific heat enhancement on solar field mass flow rate, number of receiver tubes, and parasitic

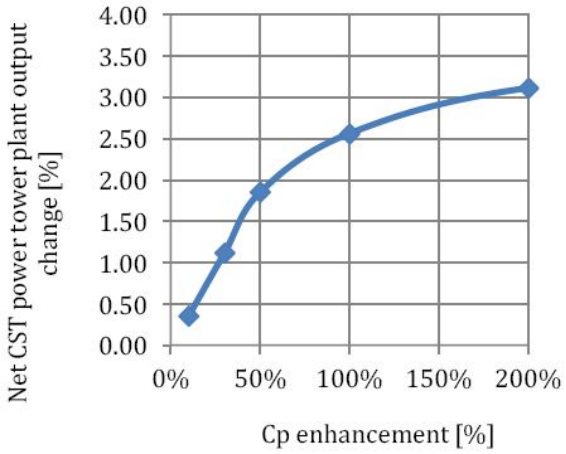


Fig. 4. The effect of specific heat enhancement on net power output of CST-tower plant.

IV. THE ECONOMIC EFFECTS OF SOLAR SALT SPECIFIC HEAT ENHANCEMENT

As shown in section 3, two main physical benefits of adding nanoparticles to solar salt were noticed: a) the reduction in storage medium volume and b) reduced pumping (parasitic) loads. To determine if there is a net economic benefit, however, the cost of the addition of nanoparticles should be taken into account.

As discussed before, when the specific heat of the salt is enhanced, the required volume of salt (and the storage unit) decreases. However, adding nanoparticles imposes some cost to the system as well. Therefore, these two restrict each other in terms of the economic limit beyond that no further enhancement in specific heat is needed. The price of solar salt itself is widely reported to be ~1USD/kg [13]. Unfortunately, there is no data regarding the commercial price of molten salt doped with nanoparticles. However, in order to investigate the economic effects of enhanced specific heat solar salt, a price range has been considered for nanoparticles. We can consider the price of silica nanoparticles at laboratory-scale today to be around 1,300 USD/kg (based on Sigma-Aldrich silica nanoparticle 637238-500G product [14]). Assuming a price reduction due to mass production, a range of 100 to 1,300 USD per kg can be estimated. Taking into account that if only 1 wt.% of particle is required, 0.01 kg silica nanoparticle is required per 1 kg of salt. Hence, the nanoparticles would cost 1 to 13 USD per kg of salt, or 2 to 14 USD per kg for the enhanced specific heat solar salt.

The economic analysis has been investigated based on the simulation results of the Gemasolar 20 MW_e plant with 15 hours storage reported in previous sections. A total salt volume of ~8,350 m^3 or ~15,200 tonnes of salt is required. Therefore, ~USD15,200,000 would be just the cost of solar salt. In fact, the sensitivitity analysis was performed for two different storage capacity to make sure that the results reported here are not sensitive to the storage capacity (e.g. storage hours or the CST-tower plant capacity). Taking into account a price range of 2 to 14 USD/kg for solar salt specific heat enhancements of 5% to 200%, as shown in Fig. 5, any salt price of more than 5 USD/kg is not economical even with achieving 200% enhancement in specific heat. Large specific heat enhancements of more than 100% is required with salt price of 2-3 USD/kg in order to see economic benefits of using high specific heat solar salt on the CST -tower plant. This shows that increase in price of salt outweighs the volume reduction of salt by enhanced specific heat. Hence, not only achieving high specific heat enhancement is important but also to have economic viability of using solar salt doped with nanoparticles, it is vital to achieve < 50-200 USD/kg mass production price.

In order to investigate what price range of salt would be economical at smaller specific heat enhancement ranges, salt price of 1.2-3 USD/kg range was considered. As it can be observed in **Fig. 6**, the higher specific heat enhancements yield a larger margin for nanosalt price premium. Specific heat enhancement of more than 60% are required to have an economic feasibility of TES system with salt price of up to 2 times the pure salt. Although enhancements of up to 30% have been reported in the literature for solar salt doped with 1wt.% silica nanoparticles, it is not clear what commercial quantities of this material would cost.

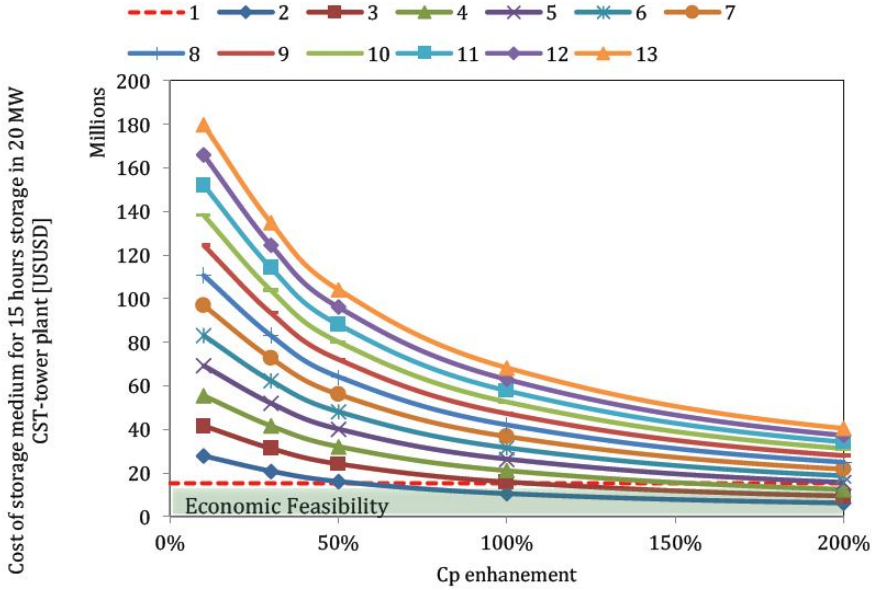


Fig. 5. Sensitivity analysis on the cost of storage medium with enhanced specific heat: 15 -hour storage in 20 MWe CST-tower plant. Considering a price range of USD2-USD13 for the salt. (Dashed line shows cost of storage with pure salt mixture).

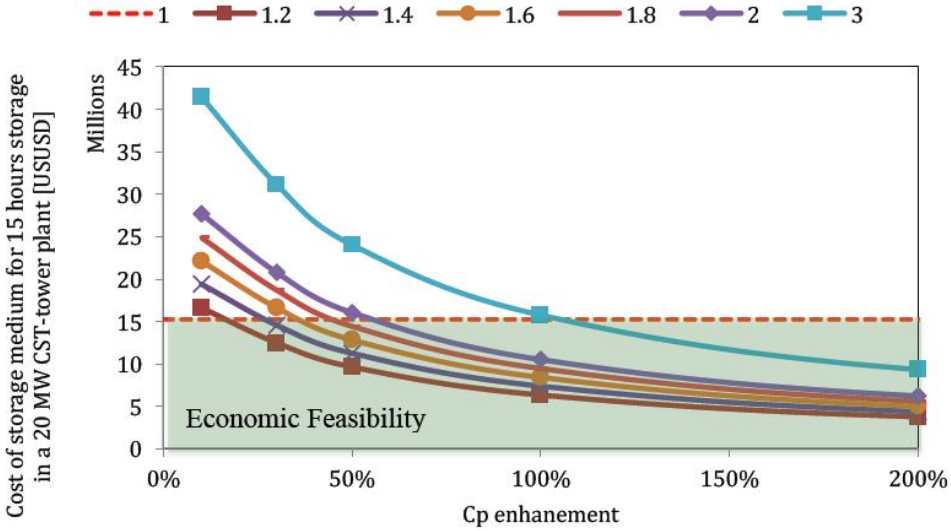


Fig. 6. Cost of storage medium (excluding tank costs) with enhanced specific heat: 10-hour storage in 20 MWe CST-tower plant. Considering a price range of 1.2-3 USD/kg for the salt. (Dashed line shows cost of storage with pure salt mixture)

If commercial enhanced specific heat salt can be produced at the price of 1.1 USD/kg, any enhancement above 20% in specific heat can be considered economically feasible. However, significant savings can be achieved by having at least 30% enhancement in specific heat and salt price of less than 1.5 USD/kg. For the specific heat enhancement of 120% (e.g. the maximum reported enhancement reported in the literature [15]), the price limit of 3 USD/kg (3 times higher than the base fluid price) represents a break-even point. Also, in these situations the tanks will be much smaller – enabling a further (structural) cost reduction. Overall this could result in significant savings in the TES costs.

CONCLUSIONS

In the present paper we have focused on the technical and economic influences of solar salt specific heat enhancement in CST plants. Considering a maximum potential specific heat enhancement of 200%, the following conclusions can be drawn from this study:

(1) The volume of storage medium can decrease by 80%.
(2) The solar field mass flowrate, number of receiver tubes, and the pumping parasitic load can decrease by up to 90%.
(3) The net power output of CST-tower plant can increase by up to 3%.
(4) Achieving 200% enhancement in specific heat of solar salt has no economic benefits if salt price is more than 5 USD/kg.
(5) Large specific heat enhancements of more than 100% is required with salt price of 2-3 USD/kg in order to see economic benefits of using high

specific heat solar salt on the CST-tower plant

(6) If reliable specific heat enhancements in the range of 20-40% are achievable, the price of the molten salt mixture could be up to 10% higher than the cost of the pure fluid. However, for a specific heat enhancement of 120% [15], the price limit is 3 USD/kg (3 times higher than the base fluid price).

It was shown that with enhanced specific heat of solar salt a huge volume reduction is possible in the TES salt tanks. However, today's (small-scale production) price for nanoparticles outweighs the economic benefit of this volume reduction. Hence it is vital to achieve cheaper mass nanoparticle production costs to obtain a real benefit from the high specific heat enhancements reported in literature for 1wt.% of nanoparticles.

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