Thermal Insulation for a High Temperature Molten Salt Storage Tank in a CSP Plant

Preprint

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Thermal Insulation for a High Temperature Molten Salt Storage Tank in a CSP Plant

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Abstract. A ternary molten chloride has been suggested as a high temperature (550-720 °C) sensible heat storage medium for a two-tank system. An effective thermal insulation is proposed to provide an opportunity for the fabrication of both the hot and cold storage tanks from lower cost metals, e.g. A240-347H, by maintaining the tank wall below 500 °C. To achieve this, the hot storage tank mainly comprises of inner shell (11.4 cm of a refractory brick as liner (KX-99®), 30 cm of insulation brick) and outer metal shell, where 5 cm of frozen layer of PCM800 (NaCl), and 5 cm of ceramic wool fill the annular space between the shells. Another layer of ceramic wool was introduced at the outer side of the metal shell to keep the temperature lower than 60 °C. ANSYS Fluent was used for the numerical study of the cool down behavior of the system during idle period when tank is quarter-filled. The heat transfer modes were considered as radiation and natural convection heat transfer from the hot molten salt at 720 °C, conduction through the solid layers and convection heat transfer from the outer shell to the environment at 15 °C. The results showed that the proposed insulation system including a frozen layer of PCM800 maintains the temperature at the metal wall lower than 500 °C, and lower than 60°C at the outer side of the tank. Apart from the insulation property of the frozen layer of PCM800, it absorbs any leak of hot molten salt, acting as a barrier between salt and the metal shell. The thermal performance analysis provide an insight into the benefits of the multilayer insulation.

INTRODUCTION

An alternative high temperature two-tank thermal storage system is a field of research interest because of its durability in the high temperatures required for the third generation of CSP plants. Considering the higher operating temperatures to achieve higher efficiency for CSP plants, Myers and Goswami [1] performed a feasibility study of 133 chloride salt systems as HTF and/ or thermal storage medium, e.g. sensible heat storage or PCM. Recently, Coventry et al.[2] studied the potential of a ternary molten chloride, a mixture of potassium, sodium and magnesium chloride as a high temperature sensible storage medium for the two-tank system.

In a likely scenario, following a ten hours of discharging, an idle phase starts. During an idle mode (e.g. between 2 am and 10 am) with no charging or discharging, the two-tanks might be semi-filled or quarter-filled. A previous study by Papanicolaou and Belessiotis [3] found that the fluid experiences three phases during a transition period; e.g. a sidewall boundary formation, stratification and equilibrium. The highest rate of heat transfer/loss might occur during the sidewall boundary formation, where the radiation, free convection and conduction occur simultaneously. The cool down behavior of a two-tank system for 880 MWh thermal storage (D=39m x H=11.7m) was numerically examined by Schulte-Fischedick et al. [4]. Using Finite Element Method (FEM) to assess the heat losses, and 2-D and 3-D computational fluid dynamic (CFD), the authors found that for the empty tank (40 cm molten salt at the bottom), it takes 3.25 days from the beginning of the idle period to the onset of freezing at the bottom corner of the tank. By including a turbulence model, the authors proposed a realizable k-ε for semi-full or empty tank, and the standard k-ε for the full tank.

In a comprehensive study, Gabbrielli and Zamparelli [5] proposed an iterative optimization procedure aiming for the least cost of a salt storage tank using carbon steel as the main shell and AISI 321H as the internal liner in contact with the salt at maximum temperature 550 °C. Thermal and mechanical (stress) analysis were used to design the tank and the insulation layers to reduce the heat loss and protect the salt from solidification. The study showed that the total investment cost and heat loss reduce as a function of the tank height. For instance, an increase from 5m to 17 m, the heat loss reduces to 30%, while a 44% cost reduction is expected.

Lang et al. [6] investigated the thermal insulation options for an ultra-high temperature Sensible-Latent heat thermal energy storage system. The storage system, a truncated cone contains an alloy of silicon and boron that can be heated up to 2000 °C, where the phase change temperature is dependent to composition. The proposed insulation consists of a gap (filled by either air, argon or vacuum), a layer of graphite fiber mat, and a microporous fumed silica board. Conducting numerical modelling, conduction and radiation were considered as the major modes of heat transfer while free convection assumed to be negligible. The result of the study showed that while using argon instead of air has less impact on the heat transfer rate, using vacuum could halve the rate of heat loss. For instance, from 1060 Watts to 533 Watts while reducing the total cost of insulation, from 1430 euro to 1398 euro.

Building upon the previous studies, this study aims to investigate the impact of a frozen layer PCM on the thermal performance of the hot tank of the ternary chloride. Additionally, the feasibility of the frozen layer PCM to act as a barrier to stop any leak reaching to the SS shell is discussed.

SYSTEM SPECIFICATION

A two-tank system is considered as a sensible heat storage containing a ternary chloride as the storage medium for which the thermophysical properties are included in Table 1. The tank size assumed to be 14 m in height and 38 m in diameter, comparable to the full-scale solar-salt tank. The ternary chloride as the sensible heat storage medium and HTF is assumed to be at 720 °C.

The desired target is no more than 2% heat loss from the full-scale tank over a 24-h period (e.g., 2 MW from a 2,800-MWh, 1195 W/m^2 TES system). In line with the minimisation of the heat loss, the insulation aims for a maximum temperature of 500 °C at the inner side of the shell, which enables the usage of lower cost metals, e.g. A240-347H. At the outer surface of the storage tank, the temperature should remain below 60 °C for safety purposes.

In a more likely scenario, following ten hours of discharging, an idle phase starts, e.g between 2 am and 10 am with no charging or discharging while the hot tank is 25% filled. Assuming 25% of the tank height is filled during the idle period, the height of the wall section is taken 3.5 m while the width of fluid layer is taken 3.5 m to capture an appreciable part of radiation and convection forming a thermal boundary layer at the wall.

Insulation

Super duty fire clay brick (KX-99®) is suggested by [7] as an interior liner in contact with molten salt. The second

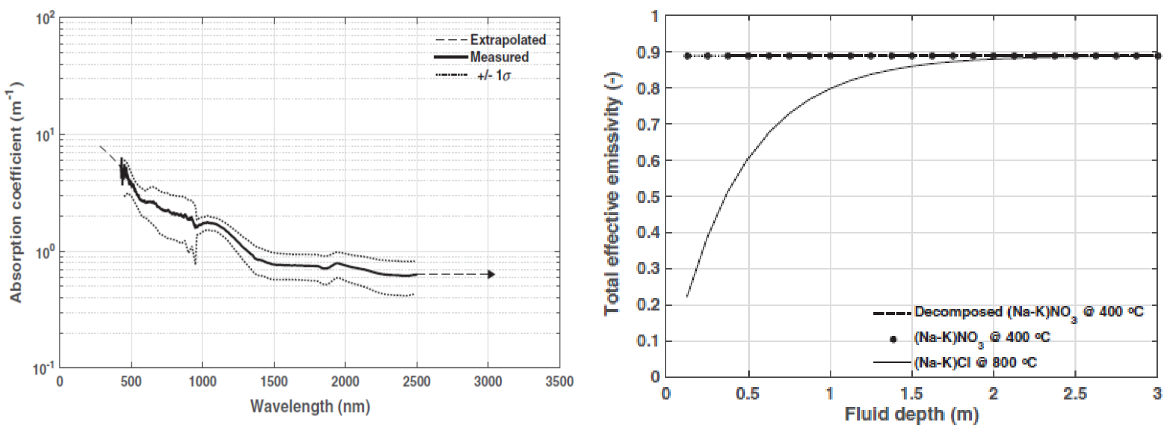
TABLE 1. Thermophysical properties and thickness of the system

material	**K, W/m K**	**Cp, J/kg K**	**ρ, kg/m3**	**melting point, °C**	**μ, Pa s**	**a, 1/m**	**Thickness, cm**
Ternary Chloride	0.31	1180	1640	387	0.0015	0.7	
KX-99®	1.5	1000	2290	-----	----	----	11.4
insulating brick	0.33	1000	769	----	-----	----	30
PCM800 (solid)	1.3	1218	1450-1700	800	----	0.7	5
Ceramic wool	0.11	880	128	----	----	----	5
Shell – 347 H	16.3	502	8030	-----	----	----	1
Ceramic wool	0.11	880	128	----	----	----	10

layer is an insulation brick, with 30 cm of the refractory brick as the major part of the thermal insulation. A layer of frozen PCM800 (sodium chloride) followed by two layers of ceramic wool at the inner and outer surface of the shell (e.g. A240-347H) were considered to complete the insulation. Table 1 shows the thermophysical properties of different layers of the proposed insulation. The frozen layer of PCM800 is proposed as an absorber of molten chloride in case of any leak through the refractory brick.

Optical Properties

At high temperatures ~ 800 °C, radiation heat transfer might be a major heat transfer mode where the optical properties of the material are required. Optical properties of binary molten salt mixtures of (40% wt. KNO3:60% wt. NaNO3) and (50% wt. KCl: 50% wt. NaCl) were experimentally examined by [8]. The results of the measured absorption coefficient for the molten chloride mixture at 800 °C is shown in Fig. 1a.



(a) (b)

FIGURE 1. Absorption coefficient of 50wt% KCl:50 wt% NaCl binary chloride molten salt at 800 °C [8]

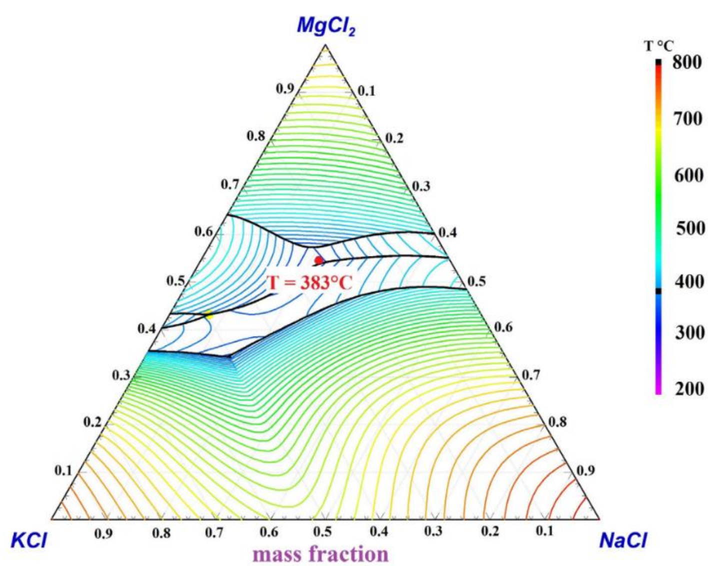


FIGURE 2. Phase diagram of NaKMg-Cl system from FactSage

Molten salts are considered as semitransparent and non-scattering media where radiation can penetrate an appreciable distance depending on the physical system [8, 9]. They display similar behavior as molecular gases (e.g.

flue gases in a furnace) in a sense that molten salt as a participating medium emits and absorbs heat to and from the tank wall. Depending on the emissivity and reflectivity of the wall (lining), heat is partly emitted/reflected back to the salt medium while partly is absorbed and lost to the environment due the conduction through the wall.

The ternary chloride and PCM800 are considered as participating media in radiation. The ternary chloride and PCM are also considered semitransparent media, where internal emissivity is dependent to the thickness. This is also shown in the graph (Fig. 1b) provided by [8], and emissivity for the semitransparent mixture of chlorides with thicknesses less than 10 cm is negligible. However, assuming the refractory brick as an opaque medium, the approximate internal emissivity is taken equal to 0.3.

Frozen PCM as a Barrier

The phase diagram in Fig. 2 shows that any interaction between the molten salt storage (NaKMg-Cl) and frozen salt layer PCM800 (NaCl) would result in a slight change in composition but is otherwise considered to be unaffected. Thus, the frozen PCM800 can be considered as a barrier to prevent any leak of ternary chloride reach the metal shell.
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NUMERICAL MODELLING

In this study for the minimization of the heat conduction/loss through the tank wall, radiation and free convection heat transfer from a layer of fluid to the wall is calculated. The molten salt layer is considered at the bulk fluid temperature at one side while radiation, and natural convection are the major heat transfer modes, conduction is minor due to the low thermal conductivity of molten salt. Conduction is the major heat transfer mode through the solid layers of the proposed insulation. It is assumed that the highest rate of heat transfer/loss occurs during the transient period of sidewall boundary formation, while radiation, free convection and conduction heat transfer occur simultaneously. Considering the first 4 hours of idle phase, the heat transfer was calculated to evaluate the evolution of the boundary layer at wall and temperature profile across the multi-layer system. Assessment of the heat transfer rate during this period provides a base for the evaluation of insulation system and the required layers and thicknesses.

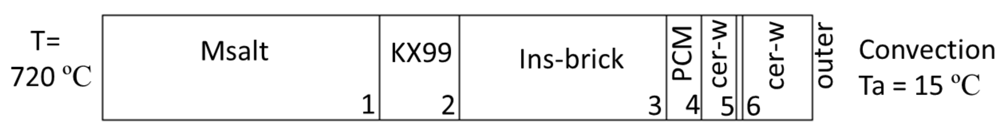


FIGURE 3. Schematic section of the sidewall of the hot tank, including the boundary conditions for steady state modelling; inner side at fixed T=720 ºC, outer side at free convection at Ta = 15 ºC, and adiabatic at top and bottom of all domains. (1) molten chloride, (2) interior liner (KX-99), (3) insulation brick, (4) PCM800, (5) ceramic wool, (6) SS shell, (7) ceramic wool.

Two Case Studies

As a first step, a small section of the wall with a height of 15 cm was considered to examine the temperature profile across the tank wall and insulation layers. The width of the molten chloride is taken 40 cm, which was enough to capture the thermal boundary layer formation. The boundary layer thickness due to internal natural convection can be estimated with Eq. (1) [10], which is much smaller than 0.4 m during the idle period.

$$\delta_T \sim (\alpha t)^{0.5} = (1.6e\text{-}7 \times 3600)^{0.5} = 0.024 \text{ m} << 0.4 \text{ m} \quad (1)$$

In the first case, there was less space in the molten chloride domain to capture the impact of convection. The second case of modelling aims to capture the impact of the convection within the tank height of 25% filled which is assumed to be 3.5 m. The width of the ternary chloride in the model was taken more than two order of magnitude larger than the boundary layer thickness to provide enough space for the temperature gradient evolution. This is to make a reasonable assumption of fix temperature at 720 ºC as the boundary condition (for the steady state) between the modelling domain and the bulk ternary chloride. It is a reasonable assumption that beyond this boundary, the wall

effect smears away and bulk molten chloride is nearly at uniform temperature equal to 720 ºC. The thickness of the insulation layers are the same as case one, while the height was taken to be 3.5 m, the same as the molten chloride. In this case, more details of the convection can be captured.
The geometry of the wall section (Fig. 3) was considered including the molten chloride as the fluid domain and other six domains of insulation/shell layers.

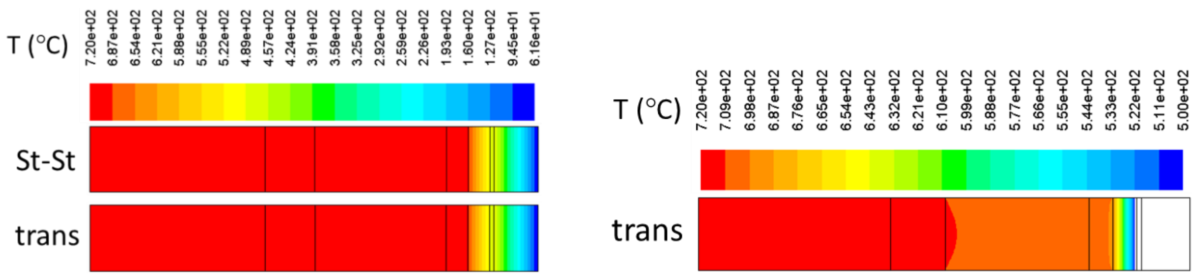
Numerical Methods

The Reynolds Averaged Navior Stockes (RANS) equations were solved for the numerical modellings. The turbulence model, realizable K-ε model, was adopted as it was suggested by Schulte-Fischedick, Tamme [4] for the quarter full tank. The enhanced wall treatment including thermal and full buoyancy effect options were included. Considering the ternary chloride as a semi-transparent and participating medium, the discrete ordinate method was selected as the radiation model.

For each of the two cases explained above, the first modelling was conducted as steady state with the initial temperature 300 ºC in all domains except for the molten chloride which was set at 720 ºC. The result of the steady state modelling was applied as the initial condition for the transient modelling. Convection heat transfer was considered as the outer boundary condition, the same as the steady state modelling. However, for the inner interface with the bulk molten chloride, a mixed convection and radiation heat transfer was considered as the boundary condition instead of fix temperature at 720 ºC. The time step was taken 0.1 seconds to start the simulations, and increased to 0.5 seconds and 1 seconds as the simulation progressed to make sure a smooth convergence.

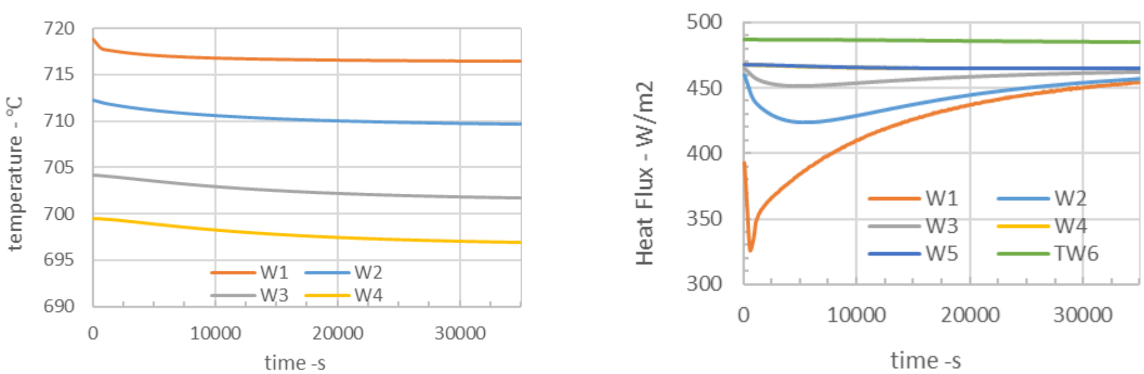
RESULTS AND DISCUSSION

Results from the two case studies provided insight into the heat transfer through the wall section, the transient



(a) (b)

FIGURE 4. Temperature profiles for the steady state (St-St) and transient (trans) modelling of case one after 10 hours: (a) temperature profile through the multilayer insulation, (b) temperature profile through the wall section just before the shell.



(a) (b)

FIGURE 5. Results of transient modelling of case one after 10 hours: (a) temperature profile at both sides (W1, W2) of the interior liner (KX99), (b) temperature profile at the both sides (W3, W4) of frozen PCM layer, (c) heat flux through the different layers of insulation.

temperature gradient evolution, and the cool down behavior of the molten chloride.

Case One

Steady state modelling of the small section (the total height = 15 cm with molten chloride width = 40 cm) of the tank was conducted. Using the result as the initial condition for the transient modelling provided insight in the evolution of temperature profiles and the cooling down behaviour during the idle stage. These results in Figure 4 show that the proposed insulation holds the temperature below 500 ºC before the shell and about 60 ºC at the outer surface. Moreover, the temperature at the PCM section is lower than the melting temperature of PCM800.

Figure 5a, and 5b show the temperature profile at the interfaces between the insulation layers. Figure 5a shows the temperature at both sides of the interior liner (KX99) drops 3 K during the 3 hours of idle stage. Here the cooling down is dependent to the amount of heat source (molten chloride with height = 15 cm and width = 40 cm) which is small relative to the real scale. Figure 5b show the same temperature drop across the both sides of the PCM800. Figure 5c shows that the maximum heat loss from the outer surface to the environment (at 15 ºC) is about 470 w/m^2.

Case Two

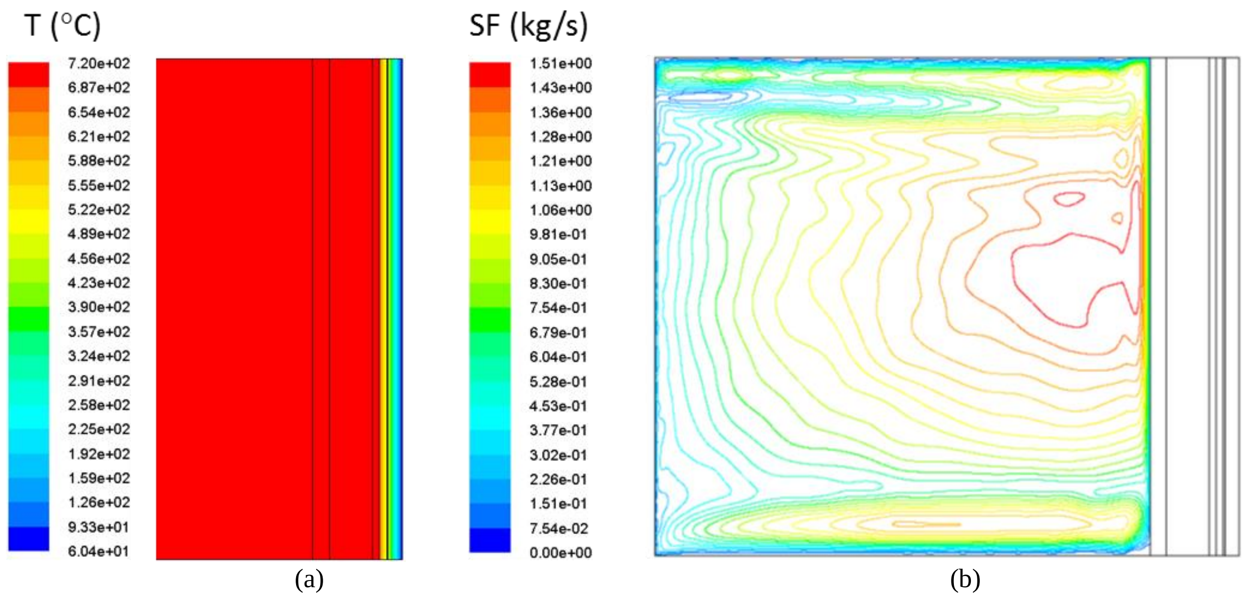


FIGURE 6. Results of transient modelling of case two after 3 hours: (a) temperature profile through the wall section, (b) stream functions through the molten chloride.

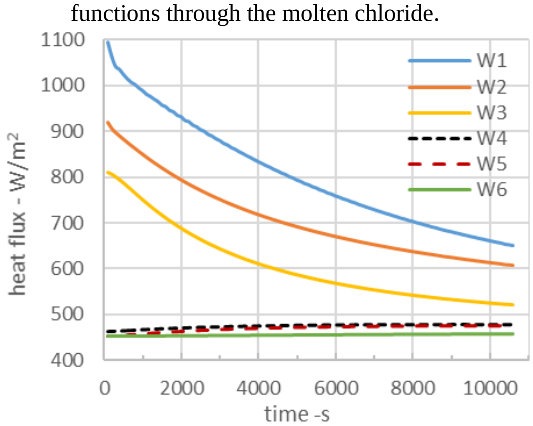


FIGURE 7. Results of transient modelling of case two: heat flux through the different layers of insulation.

The steady state modelling of case two (the total height = 3.5 cm with molten chloride width = 3.5 m) was conducted following by a transient modelling using the results from the steady state as the initial condition. Figure 6 shows the results of the transient modelling. Figure 6a demonstrates that at the scale closer to the real system, the proposed multilayer insulation is capable to keep temperature lower than 500 °C before the shell, and 60 °C at the outer surface of the tank. Figure 6b shows the mass convection which is maximum 1.5 kg/s at the interior liner. Figure 7 shows the heat loss to the environment which is almost the same as the result of case one, 470 W/m^2. This is in the acceptable range, less than 2% of the total thermal storage energy during the 24 hours as mentioned in the system specifications.

CONCLUSIONS

In the current study a multi-layer insulation solution has been proposed for a high temperature (720 °C) molten chloride storage tank. By considering the conduction, convection, and radiation heat transfer, the results of the numerical study showed that this configuration could maintain the tank wall temperature to below 500 °C, and 60 °C on the outer surface of the insulation, thus allowing lower cost metals such as A240-347H to be utilised. Furthermore, the estimated heat loss through the insulation was about 470 W/m2 during the three hours of standstill with no charge/discharge. Lastly, considering the molten salt and frozen PCM800 compositions in relation to the phase diagram, it is expected that any interaction of the molten salt into the frozen salt barrier would result in minor changes in composition but would otherwise remain unaffected. Experimental investigation is required to verify the analytic assessment.

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REFERENCES

1. Myers, P.D. and D.Y. Goswami, *Thermal energy storage using chloride salts and their eutectics.* Applied Thermal Engineering, 2016. **109**: p. 889-900.
2. Coventry, J., C. Andraka, J. Pye, M. Blanco, J. Fisher, *A review of sodium receiver technologies for central receiver solar power plants.* Solar Energy, 2015. **122**: p. 749-762.
3. Papanicolaou, E. and V. Belessiotis, *Transient hydrodynamic phenomena and conjugate heat transfer during cooling of water in an underground thermal storage tank.* Journal of heat transfer, 2004. **126**(1): p. 84-96.
4. Schulte-Fischedick, J., R. Tamme, and U. Herrmann. *CFD analysis of the cool down behaviour of molten salt thermal storage systems*. in *ASME 2008 2nd International Conference on Energy Sustainability collocated with the Heat Transfer, Fluids Engineering, and 3rd Energy Nanotechnology Conferences*. 2008. American Society of Mechanical Engineers.
5. Gabbrielli, R. and C. Zamparelli, *Optimal Design of a Molten Salt Thermal Storage Tank for Parabolic Trough Solar Power Plants.* Journal of Solar Energy Engineering, 2009. **131**(4): p. 041001-041001-10.
6. Lang, S.,B. Dominik, M. Roman, D. Harald, *Thermal insulation of an ultra-high temperature thermal energy store for concentrated solar power.* AIP Conference Proceedings, 2018. **2033**(1): p. 090020.
7. Jonemann, M., *Advanced Thermal Storage System with Novel Molten Salt: December 8, 2011 - April 30, 2013*. 2013, ; National Renewable Energy Lab. (NREL), Golden, CO (United States). p. Medium: ED; Size: 87 pp.
8. Tetreault-Friend, M.,L. A. Gray, S. Berdibek, T. Mckrell, A.H. Slocum, *Optical properties of high temperature molten salt mixtures for volumetrically absorbing solar thermal receiver applications.* Solar Energy, 2017. **153**: p. 238-248.
9. Modest, M.F., *Radiative Heat Transfer*. 2003, San Diego, UNITED STATES: Elsevier Science & Technology.
10. Bejan, A., *Internal Natural Convection*, in *Convection Heat Transfer*. 2013, John Wiley & Sons, Inc. p. 233-294.