SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Operations, Maintenance, and Component Reliability

https://doi.org/10.52825/solarpaces.v3i.2325



Published: 19 Nov. 2025

# Exergy-Based Crossover Salt Tank Protection

## A Study on Safeguards for Critical CSP Components

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**Abstract.** In recent decades, renewable energy's share in global energy production has grown, with ambitious goals set for the green transition. Concentrating Solar Power (CSP) is crucial in this shift due to its energy storage and on-demand delivery capabilities, which prevent competition with intermittent sources like wind and photovoltaic (PV) systems. CSP enhances grid stability by providing energy during low production times and storing excess energy as heat. This stored heat, at high temperatures up to 550°C, can be used in industrial processes, including green fuel synthesis. The key components in CSP systems are the salt tanks, which are vulnerable to issues like corrosion, thermal shock, and thermal deformation, as seen in several projects worldwide. These issues are often due to temperature gradients in the tanks, which can cause buckling and fatigue rupture. The study focuses on strategies to minimize these risks, particularly through innovations in Vast's CSP v3.0 design. This includes a modular solar field arrangement to reduce temperature peaks and drops, active control of molten salt flow to match heat carrier fluid (HTF) temperatures, and a robust heat exchanger to buffer temperature changes. An innovative algorithm in the valve system at the molten salt tank inlets further enhances safety by directing hot salt to appropriate destinations, addressing the temperature differential issue that could reduce the equipment lifespan. This study, based on a numerical model of the entire plant and real weather data, tested various configurations to optimize the salt tanks' working conditions.

**Keywords:** Concentrating Solar Power, Molten Salt, Temperature Gradients, Salt Tank Protection

## 1. Introduction

In the last decades, global energy production has seen a constant growth of the renewable energies share, and as the green transition continues and increasingly ambitious goals are set, new challenges arise. In this scenario, Concentrating Solar Power (CSP) represents a promising solution whose integration into the grid offers several significant benefits.

Firstly, its ability to efficiently store energy in the form of heat and dispatch it on demand addresses a large part of the intermittency issues associated with other renewables such as wind and photovoltaic (PV). Moreover, CSP can compensate for lower generation during forecasted adverse weather conditions or nighttime, and for extra consumption during the daily peak hours [1]. Secondly, as CSP plants generate electricity through a standard steam turbine and generator, they act as synchronous generators during operation and contribute to maintaining stable grid frequency. The large inertia in those components offers the opportunity to act as synchronous condensers whenever idle, this time contributing to the grid's reactive power regulation against a price. Balancing both the grid's frequency and power factor is a critical challenge, and addressing it using renewable solutions is crucial for the complete decarbonisation of the energy system. Finally, the option of shifting the production has another indirect advantage, as it avoids being in competition with PV. Being both systems sunlight-driven, they collect energy during the same timeframes, but while PV supplies power, the CSP plant can charge the molten salt tanks for later dispatch, even after multiple days. In addition, if the CSP system is equipped with dedicated salt electric heaters, it can absorb the excess energy and smoothen the generation peaks, further improving the grid stability. The electric salt heaters are characterised by a quick consumption response time [2], while, due to the considerable startup time of the turbine, dispatching is effective on multiple-hours timescale [3]. The amount of energy that can be absorbed or supplied by the system is strictly related to the total salt inventory. The storage capacity can be varied by changing the size or quantity of the tanks, offering large flexibility during design. Therefore, scalability represents another notable advantage of this technology.

For all the reasons cited so far, the salt tanks are one, if not the most important components of the system. Their availability is critical for the performance of the plant and failures would compromise the plant production, incurring in significant economic losses [4], [5], [6]. A failure of a salt tank can be due to various reasons, mainly corrosion, thermal shock, and thermal deformation [7]. The last two phenomena can be correlated with the temperature gradients in the tank, both temporal and geometric, and have higher impact at high operating temperatures or low salt inventory levels [4]. Moreover, as CSP is characterised by transients, gradients occur cyclically, and creep-fatigue rupture might occur depending on their magnitude and frequency. In this article, the focus will be on strategies to limit the thermal stresses on the tanks improving the conditions of the salt supply, acting on both the equipment design and the system’s control logics.

## 2. Architecture of a Sodium-Salt CSP cycle

Vast's CSP v3.0 technology takes elements from the Parabolic Trough Collectors plants (v1.0) and from the Concentrated Tower plants (v2.0), merging the modular philosophy with the central tower-based solar field architecture. The plant is composed of four main process areas: the solar field, which collects the solar energy through heliostats and receivers; the Heat Transfer Fluid (HTF) network, which transfers the energy in the form of heat from the receivers to the HTF/Salt heat exchanger (HX); the Thermal Energy Storage (TES) system, which stores the energy delivered by the HTF system and provides heat to the Power Island when needed; the Power Island, composed of the Molten Salt Steam Generator system (MSSG), and Steam Turbine and Generator (STG), which is finally charged of the thermal energy transformation into electricity. This last area is composed of state-of-the-art equipment, much inherited from standard fossil power plants. The main difference consists in the Steam Generator being run on Molten Salt instead of coal or gas [8].

The novelty of Vast’s CSP cycle compared to the existing plants is that the HTF system acts the interface between the solar field and the TES system. This introduces an inevitable temperature drop due to the minimum inlet temperature in the heat exchanger, but this is required by the nature of the process conditions. Using molten salt in the receiver as in the CSP v2.0 would be the obvious choice, avoiding unnecessary temperature penalties. Yet, its high viscosity would increase the requirements of the pumps, the piping would have to be maintained above freezing point (~250°C [8]) at any moment. Furthermore, its poor heat transfer properties would require a larger heat exchange area to achieve adequate receiver cooling. To overcome all these difficulties, sodium was proposed as HTF in virtue of its excellent thermo-hydraulic properties [9], and the results gathered over the 22-month operation of Vast’s Jemalong 1.1 MW, grid-synchronised demonstrator plant proved this to be a successful choice.

As in CSP v2.0 plants, salt tanks are critical components that need to be carefully managed during operation. Vast’s design includes many active and passive safety features to limit temperature gradients in such equipment. The most evident of them being the modular solar field arrangement. Due to the different distance that sodium must travel to reach each receiver, temperature peaks and drops are intrinsically reduced at each mixing point. Then, the bypass valve on the heat exchanger sodium inlet allows filtering the flow when its conditions are extreme, especially in the event of high Rate of Change (RoC) in temperature during transients. On the salt side of the heat exchanger, the salt flow is actively set to mirror the sodium heat capacity, estimated basing on the incoming temperature and flow rate, to stabilise and maximise the salt outlet temperature, while minimising the sodium outlet temperature. The minimum delta temperature is a function of the heat exchanger design and increases with its heat duty.

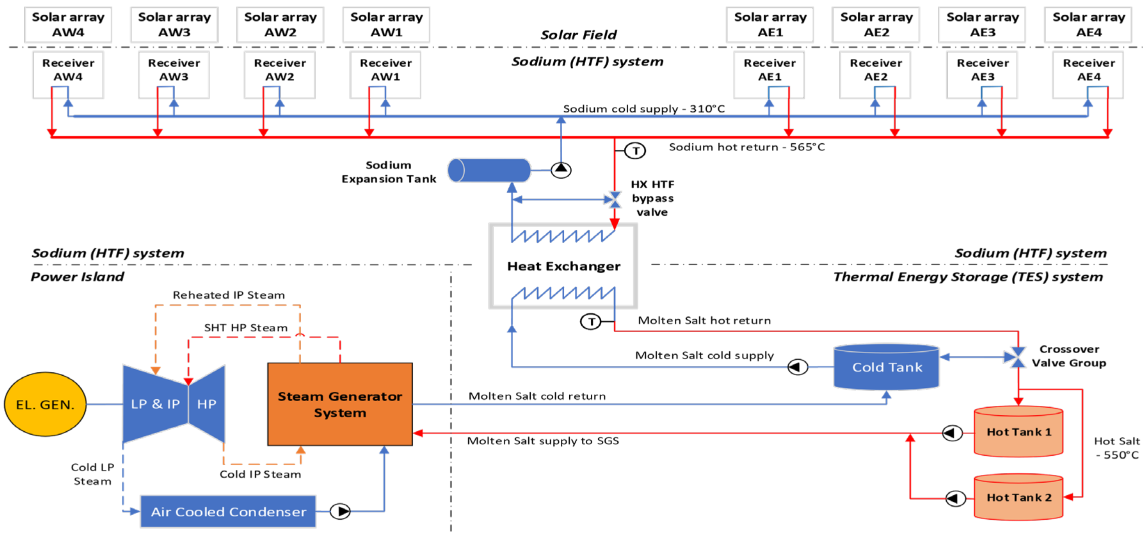


***Figure 1.*** *Simplified diagram of a modular CSP v3.0 plant using sodium as heat transfer fluid.*

Another notable safeguard is represented by a set of valves on the salt tanks inlet line, called crossover group, whose role is to divert the HX outlet salt to the most appropriate destination. While the presence of these valves is common in CSP, the innovation is rooted in the algorithm used to make the choice, which serves as the final active safety mechanism for the tank. In the literature, little interest was dedicated to this topic. Little attention has been given to this topic. It was often assumed that sparger rings would compensate for poor inlet salt conditions by enhancing mixing, or even that the dead mass of salt in the tank would absorb the excess exergy content, thereby nullifying the issue. Instead, there is reason to believe that the temperature differential between the incoming salt and the residing salt in the tank is a key driver of the lifespan reduction of this equipment [7]. CFD simulations show that cold salt tends to sink to the bottom, which might cause local temperature gradients that can cause the floor to buckle, particularly along the plate welds. Hot salt tends instead to rise limiting the issue to the walls and to creep-fatigue failure [10].

## 3. Modelling and Simulation

A numerical model of the entire power plant is established on MATLAB and focuses on the evolution in time of the various system parameters, with the goal of evaluating the thermal cycles in the equipment as a function of the input weather data. A real weather station situated in Port Augusta, Australia, provides data for the period 03/2022 - 03/2023, allowing the study of real operational conditions and weather patterns distribution. To accurately represent the cloud transients, which have a huge impact on the temperature rate of change in the receivers and the downstream equipment, 1s time resolution is chosen. In general, all systems are modelled with a 0-D philosophy, with the notable exception of the HTF network piping, which is modelled in 1-D with 1m discretisation to capture the effects of the modular solar field architecture. Valves on the HTF and salt side are modelled considering gradual flow variation during the stroking to reproduce the effects of a real actuation. Similarly, heaters are controlled considering setpoint values and hysteresis. Lastly, pumps are assumed to be able to instantaneously provide the required flow in any of the HTF and salt circuits. This is realistic as if maintained at a sufficient speed, thus always providing enough head, then the flow can be controlled in a precise and prompt way through quick-response control valves.

Particular attention is given to the HTF/Salt heat exchanger modelling. To capture the performance variation at partial loads, a parametric analysis is performed for heat exchanger inlet variables using the Flownex software. A 3D matrix is defined for interpolation with heat duty as the output. In the main code, as the primary goal is cooling the solar field HTF, the sodium side (tubes) is simulated first. The net flow after eventual bypass is determined and used to find the load case through interpolation. Subsequently, the HTF outlet temperature is calculated via energy balance. Heat losses only appear on the salt side (shell). The highest salt side outlet temperature is calculated by interpolating heat duty and inlet salt temperature. Then, heat losses are found as a function of the average salt temperature, and finally, the salt mass flow rate is calculated.

The HX HTF bypass is triggered at defined sodium temperatures, with the option of considering the rate of change as well. Also, the position of the Instrumentation and Control (I&C) on the flowpath is important. Upon sufficient distance between the sensor and the valve, the desired bypass position can be feed-forwarded to better filter unsuitable HTF flow. This reduces HX stresses and improves the salt output stability, but at a price of poorer HTF cooling and overall higher temperature of the sodium loop. An algorithm optimises the choice considering the design parameters of the equipment.

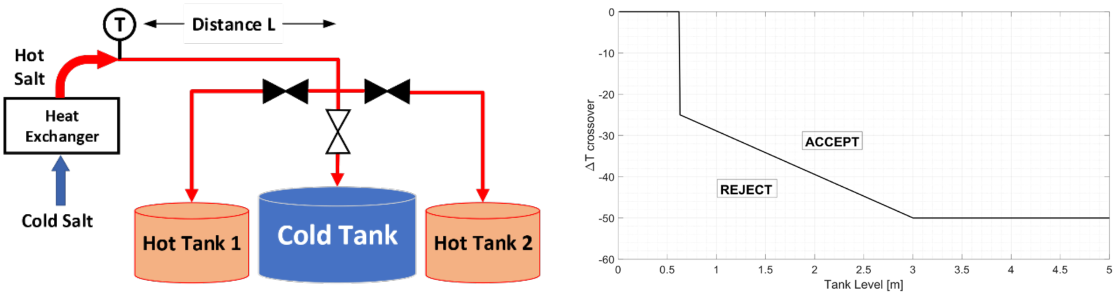


***Figure 2.*** *(a) Detail of the crossover group; (b) Criteria for salt acceptance in hot salt tanks.*

As visible in Figure 2a, the crossover group is composed by three valves, one per tank, whose positions are correlated. The crossover group state “open” allows flows into the cold tank, and this is the default command of the group, to protect the hot tanks. For this study, the supply and depletion of the hot tanks is set to be sequential, so only one hot tank can be filled or emptied at the time. When the crossover group state is “close”, the flow is diverted to the active hot tank opening the appropriate valve. At all times one valve must be opened, so the incoming salt flow can be diverted to at least one tank. The I&C equipment is located at the heat exchanger outlet, to allow the crossover group to get into the right position for when the incoming salt would reach the valves. The transit time of a fluid particle is the time required for it to travel from one point to another on the line, and it is a function of the fluid velocity and the pipe length: the higher the transit time, the longer the interval for the valves to adjust their position.

The goal of the logics commanding the crossover group is minimising the stresses in the hot tanks. Each tank is provided with a mixing system, with the aim of homogenising the internal salt temperature after the inlet. It cannot be excluded that small areas where the inlet salt does not mix occur. The temperature difference between the inlet salt and the stored salt is vital for the distribution strategy, as it represents the potential stresses that the slug could create when it reaches the tank. Then, the salt level in the tank must be considered: the higher the salt stored, the larger the volume for the inlet salt to be dispersed into, improving the chances of mixing and mitigating the effects of low-temperature slugs. The proposed approach considers both parameters, making the acceptable salt temperature a function of the salt level in the active tank, as described in Figure 2b.

***Table 1.*** *Reference case input data for HTF and Salt systems.*

| **HTF** | **Units** | **Value** |
|---|---|---|
| Valve stroke time | [s] | 30 |
| I&C distance to valve group | [m] | 70 |
| Temperature rate of change (RoC) limit | [K/s] | 0 |
| Temperature limit for acceptance in HX | [C] | 310 |
| **Salt** | **Units** | **Value** |
| Valve stroke time | [s] | 32 |
| I&C distance to valve group | [m] | 40 |
| HX heat transfer time constant | [s] | 1 |
| Max absolute crossover ΔT | [K] | 50 |

Considering the same control logic, many parameters impact the quality of the tanks' inlet salt, both on the HTF and salt sides. A parametric study is performed to quantify their impact. The conditions for the reference case are summarized in Table 1. A note to be made is that the temperature and RoC limits on the HTF side of the HX are thresholds used to reduce the stresses on the equipment, which can have the secondary effect of stabilising the salt temperature. The same holds true for the allowable ΔT for the hot salt tanks: the smaller the ΔT, the lower the stresses on the tanks. Nevertheless, bypassing flow from the HX or the hot salt tanks lowers the overall production of the plant. Those parameters can be fine-tuned during operations, instead the HX time constant depends on the exchanger design. It inversely represents the velocity of the heat transfer: higher values cause a slower transfer that smoothens the temperature spikes, but at the cost of increased thermal stresses.

## 4. Results

For each simulation, the performance of the salt supply system is evaluated observing the salt supply events in the tanks. An event is defined as: a continuous salt flow with continuous cooling or heating effect. Each event introduces a variable quantity of mass into the tank, with variable temperature and flow rate over its duration. The potential of causing thermal stresses on the system depends both on the quantity of heat exchanged and the temperature at which the heat transfer happens. This can be expressed using the exergy expression:

$$B_i = \left(1 - \frac{T_t}{T_i}\right) * Q_i \quad [J] \tag{1}$$

Where $T_t$ represents the average temperature of the salt in the tank, and $T_i$ the inlet salt temperature. Severe events can also happen over short periods with small total exergy, depending on the dynamic of the supply and on the tank level. With this perspective, a critical parameter to observe is the temperature variation during the event. As surges and dips can occur, the average temperature must be multiplied by a factor that considers the maximum temperature difference of the event against the design one:

$$\Delta T_{eq}{}' = \left(\frac{\Delta T_{max,event}}{\Delta T_{event,design}}\right) * \Delta T_{avg,event} \quad [K] \tag{2}$$

Then the level must be considered, as the lower the level, the bigger the risk of incomplete mixing when the inlet salt reaches the inner surfaces of the tank. Including it in (2) gives back:

$$\Delta T_{eq} = \left(\frac{L_{design}}{L_{min,event}}\right) * \Delta T'_{eq} \quad [K] \tag{3}$$

Critical events are expected to have high exergy, and high equivalent $\Delta T_{eq}$. The lack of one these conditions might be seen as a mitigation to the severity of the event. Ideally, a well-designed system would present events with low exergy and low equivalent temperature difference for all tank levels. Particularly when the tank is almost empty.

## 4.1 Distribution of events

The numerical simulation provided the profile of the salt supply to the tanks and their level. Then, the stress on each tank was evaluated in terms of number of events and their severity. The same approach was followed for all tanks, with emphasis on Hot Tank 1. As stated before, low-temperature events are not considered a threat for the integrity of the tank as it is supposed designed for. Similarly, low-exergy events are not dangerous because their damage capacity would be nullified before they could reach the tank walls. The exergy considered as a threshold is 1 MJ, as it corresponds to 1 minute of full flow at the maximum design ΔT. Under this assumption, Figure 3 shows that critical events concentrate between 100 MJ and 100 GJ.

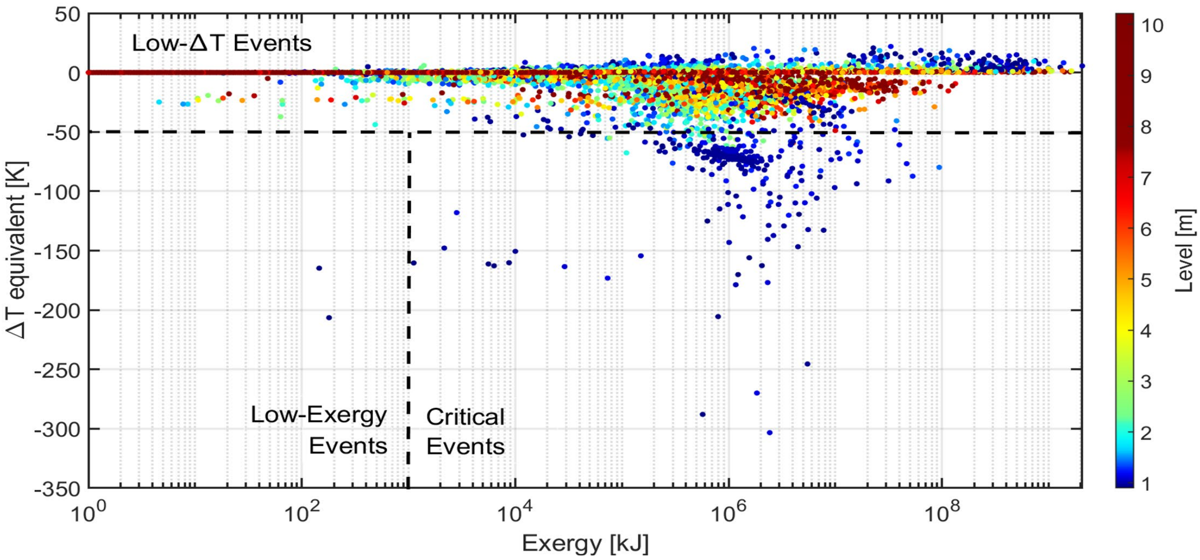


***Figure 3.*** *Salt flows into Hot Tank 1 for one year of simulation. Occurrences classified by equivalent ΔTeq, cumulative exergy of the event ΔB, and initial salt level in the tank Lmin,event.*

Interestingly, all of them happen at low tank levels, suggesting that the $\Delta T_{eq}$ is mainly driven not by large temperature differentials, but by unfavourable salt levels. As expected, events rarify with increasing $\Delta T_{eq}$ and exergy. An area denser of events exists at 0.6-2 GJ and about -75K, and it seems the results of a similar situation repeating many times over the year. Considering the zone of low ΔT events, a trend at -25K is particularly clear at low exergy values. This supposedly relates to the low-level ΔT limit, which is 25K, but differently to the previous situation the events happen at various tank levels. In general, events can reach 1 TJ of exergy, but to cumulate this much, a long event duration is requested, as the general $\Delta T_{eq}$ stays low. This suggests that such events likely occur during clear days or with very limited shading. Figure 4 gives further insights to the relationship between distribution of the events and type of day (transient/clear).

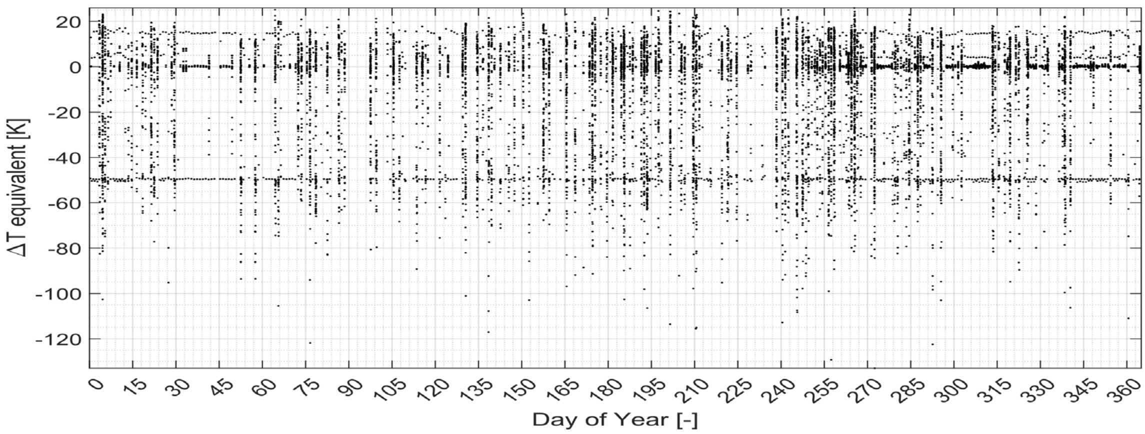


***Figure 4.*** *Daily salt flow events in Hot Tank 1 over the simulation period, and their relative equivalent temperature difference ΔTeq.*

For example, observing days 30 to 45, the number of events is extremely limited and well-fitting the design values. It suggests that those days have sunshine as per the design assumptions. The crossover group does not have to adjust its position often and that almost eliminates the misdirection of flow to the wrong tank. A different pattern is visible in most of other days, developing in the vertical direction with several events distributed all over the $\Delta T_{eq}$ range. These events are likely to belong to transient days. Days 90 to 100 feature no events at all in Hot Tank 1, suggesting a stop in heat accumulation due to insufficient solar radiation. Comparing with the DNI data confirmed values in line with these conclusions.

## 4.2 Parametric analysis

The impact of each parameter on the system performance is evaluated over the range of exergy and $\Delta T_{eq}$. The rate of changes on a generic parameter *p* is defined as the variation of exergy or temperature differential caused by a variation of one unit of the parameter *p*. Covering numerous parameters, this analysis does not aim to detail the relationship between each one of them and the observed variables, focusing on the incidence by order of magnitude. Minimum and maximum values refer to single events, while averages are calculated over the ensemble. Results are summarised in Table 2 for exergy and Table 3 for equivalent temperature difference, both excluding the limit on the rate of change at the HTF inlet of the heat exchanger as an independent parameter. This parameter was intended to prevent HTF from flowing into the HX whenever the temperature profile was varying too quickly. To obtain appreciable change on the HX inlet temperature, high RoC values were required (>10K/20s) that caused significant flow bypass. The HTF expansion vessel average temperature increased with positive feedback behaviour that systematically tripped the plant even on short transients. Thus, the impact of this parameter on the HX salt output quality can be assumed negligible. An alternative strategy to limit the RoC at the HX inlet could be sequential heliostats defocus.

***Table 2.*** *Summary of exergy range and rate of change as a function of selected parameters.*

| | | | **ΔB avg** | **ΔB max** | **ΔB RoC** | **ΔB RoC avg** |
|---|---|---|---|---|---|---|
| **Parameter *p*** | **Range** | **Units** | [GJ] | [GJ] | [MJ/*p*] | [MJ/*p*] |
| HTF HX T limit | 300−340 | [C] | 1.9 / 2.5 | 16 / 28 | 0.1 / 64 | 29 |
| HTF I&C dist. | 14 − 140 | [m] | 0.4 / 3.7 | 1.8 / 19 | -52 / 43 | 42 |
| HTF stroke t | 15 − 60 | [s] | 1.7 / 1.9 | 16 / 16 | -9.0 / 0.1 | 5 |
| Salt I&C dist. | 10 − 80 | [m] | 1.9 / 3.3 | 16 / 30 | -72 / 18 | 37 |
| Salt stroke t | 10 − 96 | [s] | 0.1 / 12 | 1.0 / 107 | 78 / 154 | 108 |
| HX constant t | 0.5 − 5 | [s] | 1.7 / 2.5 | 15 / 28 | 14 / 646 | 331 |
| Crossover ΔT | 10 − 100 | [K] | 0.1 / 48 | 0.3 / 213 | 45 / 920 | 277 |

***Table 3.*** *Summary of equivalent temperature difference range and rate of change as a function of selected parameters.*

| | | | **$\Delta T_{eq}$ avg** | **$\Delta T_{eq}$ min** | **$\Delta T_{eq}$ RoC** | **$\Delta T_{eq}$ RoC avg** |
|---|---|---|---|---|---|---|
| **Parameter *p*** | **Range** | **Units** | [K] | [K] | [K/p] | [K/p] |
| HTF HX T limit | 300−340 | [C] | -87 / -61 | -215 / -77 | 0.6 / 1.7 | 1.0 |
| HTF I&C dist. | 14 − 140 | [m] | -88 / -67 | -385 / -215 | -0.2 / 0.3 | 0.2 |
| HTF stroke t | 15 − 60 | [s] | -84 / -78 | -216 / -215 | -0.3 / -0.1 | 0.2 |
| Salt I&C dist. | 10 − 80 | [m] | -100 / -61 | -306 / -70 | -0.6 / 0.9 | 0.7 |
| Salt stroke t | 10 − 96 | [s] | -81 / -73 | -215 / -112 | -0.3 / 0.1 | 0.1 |
| HX constant t | 0.5 − 5 | [s] | -83 / -61 | -217 / -78 | 1.2 / 17.5 | 9.6 |
| Crossover ΔT | 10 − 100 | [K] | -119 / -39 | -259 / -83 | -1.2 / -0.2 | 0.8 |

Amongst the other parameters, the most relevant for reducing the severity of the supply events in the tanks are the crossover group stroke time and distance to the I&C, the Salt acceptable ΔT for the hot tanks, and the HX time constant. They all offer benefits in terms exergy and $\Delta T_{eq}$ reduction with minimal drawbacks. In particular, the HX seems to have the largest stabilisation potential, although it could be challenging to leverage due to the many compromises needed to balance thermomechanical resistance and thermo-fluid dynamic performance. Reducing the acceptable ΔT in the hot tanks is a direct way to reduce the events exergy and $\Delta T_{eq}$, redirecting the unsuitable flow to the cold tank, thus keeping the energy inside the system. This minimises the performance drop, but still has some flaws, as the cold tank design temperature must increase, and hotter salt entering the HX causes higher average temperatures on the HTF side. Considering the crossover group, a variation in the actuation time impacts the total exergy of the event up to 20 times more than the other parameters, despite not having relevant effects on the $\Delta T_{eq}$. A synergy exists with the distance from the I&C instrumentation, as increasing the transit time to the valve allows the system to better anticipate the optimum position for each flow condition. Optimising both parameters seems to be a promising approach. Conversely, the HTF valve stroke time and the preceding pipe length seem to have a negligible effect. Notwithstanding a lower influence of the HTF-related parameters on the salt outlet conditions, the HTF acceptable temperature in the HX shows the second highest RoC of $\Delta T_{eq}$. The drawback associated, all similarly to the RoC limit mentioned above, is that the average HTF temperature increases. This reduces the system capacity of absorbing transients and increases heat losses, thus reducing the overall plant performance.

## 5. Conclusion

This study examined the performance of Vast's CSP v3.0 system against the most relevant parameters in terms of hot salt generation and distribution. The approach for the analysis was based on the identification of salt supply events with significant potential of damaging the hot tanks. Such events were classified by exergy content and equivalent temperature difference between the inlet salt and the residing salt in the tank. The observed distribution of events highlighted an area at higher concentration of critical events, comprised betweend 100MJ and 100GJ. All dangerous events were cooling events, with heating events having much lower and uniform temperature differentials. Also, all critical events appeared to belong to transient days. Clear days were consistently generating a limited amount of events with high exergy and low $\Delta T_{eq}$. Amongst the examined parameters, the most impactful on the system behaviour were on the salt side of the system. Changes in the HTF parameters were causing minor improvements at a cost of performance loss and reduced ability of the system to absorb flux variations in the solar field. Notably, the rate of change of the HTF temperature was excluded from the analysis as it was not effective in either limiting the stresses on the HX or stabilising the HTF inlet temperature. Furthermore, the temperature profile in the HTF network appeared to be dominated by the modular configuration of the solar arrays, which showed a dominant effect over any other stabilisation measure. The heat exchanger time constant was proved to be the most effective parameter in terms of temperature stabilisation, despite introducing increased stresses in the equipment and having a limited range of possible values. Another relevant parameter was the maximum temperature differential allowed by the crossover group logic. Decreasing it would both stabilise the equivalent temperature differential of the flow in the tanks and reduce the exergy inlet, while slightly decreasing the plant production. The last couple of parameters also related to the crossover group, but on the mechanical side, with an interesting synergy. The valves stroke time showed high impact on the event exergy, while the distance from the I&C greatly affected the temperature differentials. Such parametric analysis was performed on both tanks, and similar trends for all parameters were observed. Nevertheless, due to the filling and depleting logics, Hot Tank 2 was observed experiencing fewer and less critical events. The cold tank showed extremely high temperature differentials for heating event only. Despite the assumption of hot salt rising by natural buoyancy, further studies should be performed to ensure that such events do not constitute a risk over the lifetime of this equipment.

Overall, this research underscores the importance of integrating advanced control strategies and passive safety mechanisms to maximize the efficiency and longevity of CSP systems, paving the way for more efficient and robust solar thermal energy solutions.

## Author contributions

Both authors conceived the presented idea. F.A. developed the crossover logics, established the numerical model and performed the simulations. K.D. verified the physical methods and encouraged F.A. to investigate the impact of the stroke time of the bypass valve, and of the heat transfer time constant of the heat exchanger. K.D. supervised the overall findings of this work, while F.A. discussed the results and redacted the final manuscript.

## Competing interests

The authors declare that they have no competing interests.

## Funding

This research was partially funded by the Australian Government through the Research and Development Tax Incentive.

## Acknowledgements

The authors thank our colleagues at Vast Renewables Ltd for their generous support, shown in many ways during this study.

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