DEVELOPMENT AND TESTING OF AN INNOVATIVE MW-SCALE HIGH-TEMPERATURE MOLTEN-SALT POWER-TO-HEAT UNIT

Summary

Electrification of high-temperature heat requires power-to-heat (PtH) systems converting variable renewable electricity into dispatchable thermal energy. This work presents the development and comprehensive experimental characterization of a 1 MW two-stage electric heater for Solar Salt (290–565 °C). The design combines proven molten-salt heat-exchanger components with modified flow guidance and advanced baffle geometry to intensify heat transfer and prevent local overheating. Independently controlled stages, dual temperature-control modes, heat tracing, freeze protection, and automated sequences enable flexible operation under fluctuating power input. The heater is integrated into a representative MW-scale molten-salt test facility with full balance-of-plant and control interfaces. This work addresses the shortage of public MW-scale data for molten-salt PtH up to 565 °C and is relevant to industrial heat electrification, CSP/PV hybrid systems, thermal storage charging, Carnot batteries, and grid-supporting services. Comprehensive experimental results will be presented.

Keywords: power-to-heat, molten salt, electric heater, CSP/PV hybrid, thermal storage, ramping, frequency services, electrification

Field of application for the findings: Sustainable Heat for Industrial Process (High Temperature Heat for Industry, Simulations, Digitalization), Electrification (Power to X), Thermal Energy Storage (Carnot Battery)

Addressed audience: Researchers and engineers in power-to-heat systems, molten-salt thermal storage, industrial heat electrification, plant design and control, hybrid renewable energy systems, and grid integration

1. Introduction

Electrification of high-temperature heat is an important route for decarbonizing industrial energy demand and increasing the flexibility of renewable energy systems. Molten-salt PtH systems are especially attractive where renewable electricity is coupled to thermal energy storage, hybrid CSP/PV concepts, or Carnot-battery configurations requiring heat at temperatures up to about 565 °C. At the same time, publicly available and bankable data for MW-scale molten-salt electric heaters under dynamic operation remain limited (Prenzel et al., 2024; Trevisan et al., 2025).

Within a publicly funded collaborative project, a modular 1 MW electric heater has therefore been developed as a high-temperature PtH unit for flexible coupling of renewable electricity to molten-salt storage and heat supply. Beyond its relevance for hybrid solar plants, the concept is directly applicable to renewable charging of thermal storage and to electrified high-temperature heat provision for industry. This work presents the heater concept, its control and protection philosophy, the integration into a representative molten-salt test environment, the test results and the simulation-assisted characterization used to define the operating window.

2. Methods

2.1. Heater design

The molten-salt electric heater comprises two resistive stages in series and is designed to heat Solar Salt (60 wt% $NaNO_3$ / 40 wt% KNO_3) from 290 °C to 565 °C at a nominal mass flow of about 2.4 kg/s. Stage 1 provides about 630 kW and raises the salt temperature to about 465 °C, while Stage 2 adds up to about 370 kW to reach the nominal outlet temperature of 565 °C. The design builds on the geometry and manufacturability of proven molten-salt heat-exchanger components, while introducing modified internal flow guidance and advanced baffle type to intensify heat transfer and avoid stagnation or dead zones that cause local hot spots and heater damage. In this way, the design aims at safer operation, improved thermal uniformity and reduced specific cost through a compact heat-transfer surface. Both stages contain parallel sheathed heating elements and multi-point instrumentation for salt temperature and element-skin temperature monitoring. The complete unit is mounted on a transportable skid integrating electrical and control cabinets, while all salt-wetted components are fully heat-traced and insulated for freeze prevention and heat-loss reduction.

2.2. Control and protection concept

The outlet temperature of the PtH unit is controlled in two ways. The flow-based control adjusts the mass flow in a cascade control structure with feedforward capability to offer flexible adaptation to fluctuating renewable-electricity availability. The power-based control is designed to adjust the two electric heater units either simultaneously or independently, with the objective of optimising start-up, shut-down and standby operations.

In addition to this control, the local programmable logic controller (PLC) includes protections, sequences, operating modes, permissives and other logics to allow safe operation and enhance monitoring and functionality. Among others, the electric heater is triggered to shut down in an emergency when critical parameters are exceeded, such as the heating element skin temperature or the salt temperature rate of change. Heat tracing is foreseen for preheating and freezing prevention. Hot standby mode at minimum load enables rapid load ramp-up from hot conditions.

2.3. Integration into the test infrastructure and simulation-assisted test preparation

The heater is integrated into a representative MW-scale molten-salt test facility as shown in Fig. 1 through a compact balance-of-plant assembly comprising inlet and outlet piping, a main flow meter, control valve, isolation valves, flexible compensators, and inlet/outlet temperature measurement. PLC interlocks define the interface between the heater controller and the loop controller for permissives, trips and setpoints. Weather protection is included for outdoor operation in order to safeguard insulation and cabinets. A pressure-assisted drainage concept is implemented to ensure full drainability despite the elevated tank connections of the existing infrastructure. This avoids the need for an additional support structure of about 4 m height and thereby reduces cost, wind load and installation complexity. Before hot-salt operation, water-loop tests of the main flow meter were used to de-risk controller tuning and validate the measurement chain. In parallel, a physics-based model of the heater is developed to support simulation-assisted preparation of the test campaign. The model is used for controller pre-tuning, assessment of operational limitations, evaluation of ramping strategies and development of the hot-test matrix over the full design temperature and load range.

Fig. 1: The power-to-heat unit prototype with a two-stage electric heater integrated into the test loop with two tank TES.

3. Results

Fabrication of the heater, skid assembly, balance-of-plant integration and implementation of the control and safety logic are completed. Commissioning and operational verification confirm the mechanical fit-up of the integrated system, electrical functionality, sequence execution, instrumentation plausibility, communication between local and plant-level control, and successful implementation of the drainage concept and tests.

Metering checks provide a stable basis for the subsequent tuning of the hot-salt control loops.

The simulation environment reproduces the dominant thermal-hydraulic dynamics required for controller pre-tuning and identifies clear differences in ramp-up behaviour between the two temperature-control strategies. Analyses indicate that the time required to reach nominal outlet temperature depends not only on whether power-based or flow-based control is applied, but also on the selected initial mass-flow ramp profile (Fig. 2). An initial ramping strategy of about 25 K/min is adopted as a lifetime-conscious operating value, while alternative ramp profiles are evaluated within the same framework. The resulting operational concept defines the admissible combination of power, flow and temperature trajectories, includes standby operation at minimum load for rapid reheating, and establishes protection margins against element overheating and salt freezing. Taken together, these test and simulation results provide the experimental and digital basis for systematic design and operation of multi-MW-scale PtH units over the full design temperature window up to 565 °C and across the intended load range, while directly addressing the needs of flexible renewable heat charging and ramping-oriented operation.

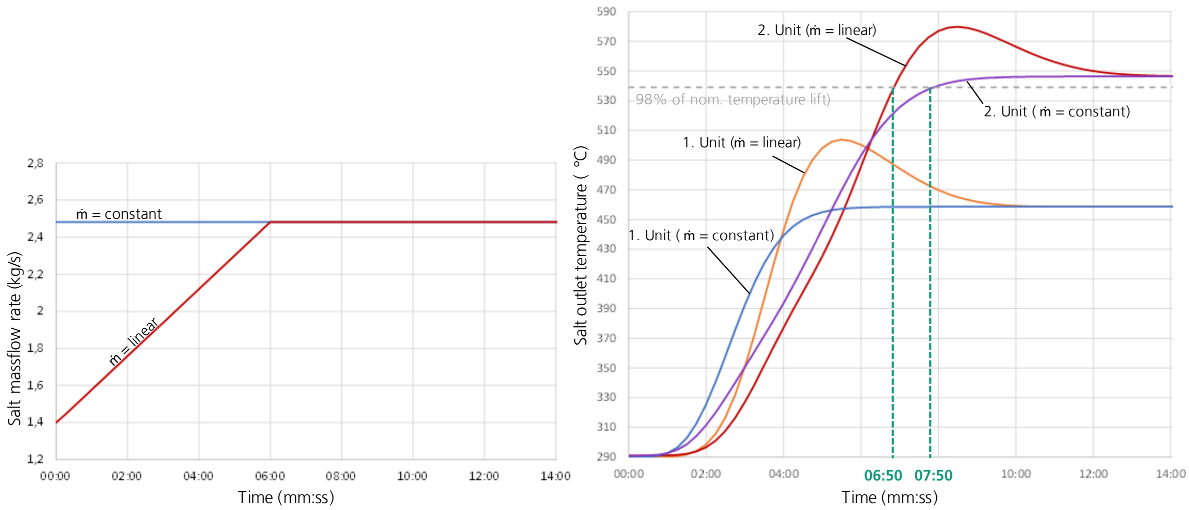

Fig. 2: Ramp-up analysis to nominal outlet temperature with different initial mass-flow ramp profiles. (Temperature overshoot due to Epsilon limitations and decoupled heating/thermal inertia modelling.)

4. Conclusions and Outlook

A two-stage, MW-scale, molten-salt electric heater for high-temperature PtH conversion has been developed, fabricated, integrated, and tested in a representative molten-salt test infrastructure. The experimental campaign evaluates thermal performance, control response, and operational flexibility across the full design range from 290 °C to 565 °C. In comparison with conventional approaches, the design achieves improved heat transfer, reduced hot-spot risk, lower specific cost and easier operation. The work closes an important gap between small-scale prototype heaters and future 50–100 MW applications by establishing both a physical test platform and a simulation environment for systematic operational assessment. Its relevance extends beyond CSP/PV hybrid plants to renewable industrial heat, thermal storage charging, and Carnot batteries. The presented development therefore contributes to the broader electrification of high-temperature heat and to the integration of variable renewable electricity through dispatchable thermal infrastructure. Comprehensive experimental characterization results will be presented.

5. References

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