SAND2019-5134C

Operational Modes of a 2.0 MW_{th} Chloride Molten-Salt Pilot-Scale System

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1. Introduction

Molten-salt technology using nitrate salts in tubular external receivers is the current state-of-the art CSP technology and operates at hot-salt temperatures of about 565 °C. Currently, there are three commercial molten-salt power towers that use sodium/potassium nitrate, or "solar salt," as both the heat transfer fluid (HTF) and thermal energy storage (TES) medium: Gemasolar (Spain, 19 MW_e, 15 hours TES [1]), Crescent Dunes (Tonopah, Nevada, 110 MW_e, 10 hours TES [2]), and Noor III (Ouarzazate, Morocco, 134 MW_e, 7 hours TES). The limit of solar-salt thermal stability is around 600 °C with ambient air as the cover gas. Slightly higher limits may be possible with solar salt, but to fully realize SunShot efficiency goals of \$15/kWh_{th} HTFs and an LCOE of 6¢/kWh [3], molten-salt technologies working at higher temperatures (e.g., 650 °C to 750 °C) will require an alternative salt chemistry composition, such as chlorides. Subsequently, the "Gen 3 Liquid-Pathway" team, comprised of various research institutions, and led by the National Renewable Energy Laboratory (NREL), are developing a concentrating solar power (CSP) system to be developed to advance molten-salt systems technology from the current state of-the-art solar-salt/Steam Rankine design embodied by industrial plants [2] operating at 565 °C and ~42% thermo-electric conversion efficiency, toward a next-generation salt or alkali metal HTF capable of interfacing with a supercritical carbon dioxide (sCO_2) Brayton cycle operating at 720 °C and ~50% efficiency. A thermodynamic system model for a 2-MW_{th} molten-salt test loop has been developed with a target receiver temperature of 750 °C, with hot and cold tank temperatures of 720 °C and 500 °C respectively. The system design includes TES of 6 hours, based on a 8.0 kg/s mass flow rate and a 36,000-gallon salt inventory. In this investigation, engineering design has been performed for the system design of a Pilot-scale molten salt test loop to be operated at the Sandia National Laboratories National Solar Thermal Test Facility (NSTTF), where several operational modes according to Fig. 1 were developed for both steady state and transient scenarios, ranging from start-up and nominal steady operation, to shut-down and idle processes. The preliminary results of this work have shown that higher system performance, by as much as 10% can be achieved, under nominal steady operation with a ternary 20%NaCl/40%MgCl/40%KCl weight percent chloride salt composition, versus that of a previously considered 32%MgCl/68%KCl mole percent salt composition. This result assumes ideal receiver absorption and heat exchanger heat transfer. This research also includes NREL System Advisory Model (SAM) research that investigates predicted performance for a scaled 100-MW_{Net} power tower system, employing the ternary chloride salt chemistry, operating under the same steady and transient operational modes.

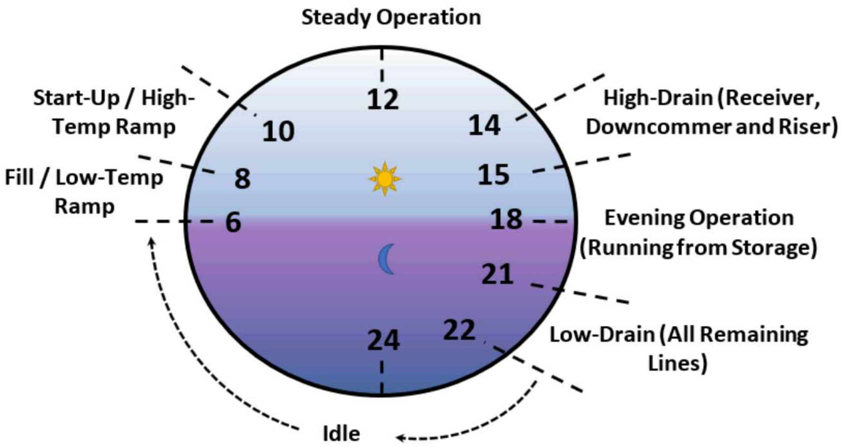

Figure 1. Gen 3 Liquid-Pathway molten salt operational modes based on a 24-hour period.

2. System Process design modelling

A thermodynamic system design model was developed using Engineering Equation Solver (EES) where state properties were calculated at inlets and outlets along both hot and cold legs of the pilot-scale plant. For this

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

investigation, both steady-state and transient models were developed pertaining to respective operational modes of the thermal-hydraulic system. This model was constructed from a series of subroutines that were integrated in a top-level file to solve a closed a set of equations. Models are set up together in pairs, with a component model having an odd inlet state index (i.e., 1) and set up to solve for its even outlet state index (i.e., 2) and followed by a piping model which uses the previous even outlet state as its inlet state, which then solves for its odd outlet state (i.e., 3). This simplifies tracking component and piping model results based on their inlet state index. User-supplied inputs and calculation settings are supplied through the EES diagram window and via lookup tables, as well as parametric tables as appropriate for the solution configuration. Data from any user input method can be saved to and loaded from a file to simplify scenario modeling without requiring multiple copies of the EES code itself. The EES model was developed to be configurable to facilitate parametric studies related to pump design, heat exchanger design, etc. Operational modes considered in this study include six principle modes pertaining to Pilot-scale sequences for transient start-up and shut-down, as well as steady-state operation:

1. Fill of the riser, downcomer and receiver with low-temperature ramp-up,
2. Start-up and high-temperature ramp-up of systems and components,
3. Steady operation,
4. Drain operation of system high-level lines and receiver,
5. Drain of all lower-level system lines, and
6. Idle operation of cold tank and remaining wet components.

Additionally, included are two modes pertaining to contingencies, which are important to consider with regard to freeze conditions or leaks, such as may occur in liquid-HTF systems. For this investigation comparison studies will be performed across all operational modes to assess impacts related to total dynamic head (TDH) and pressure drops across major components, such as the receiver, heat exchanger, downcomer and riser. The TDH values are used for sizing of respective system and pump operational curves. The total length of piping used in the system is tentatively calculated to be 833 ft (254 m) with a 2.5-inch schedule 80 (2.323-inch inner diameter), Inconel 617 nickle-based alloy for the hot leg, and a stainless steel SS347H for the cold leg. Heat losses along the respective flow-legs will be evaluated with respect to total system efficiency.

A final analysis will also be conducted using the data generated from the pilot-system to assess a scaled commercial-scale model to achieve the SunShot goal of 6¢/kWh electricity from CSP [3]. The ternary chloride salt was considered due to its lower melting point, higher heat capacity, and lower cost than binary chloride salt chemistries, where other salts have been shown to be too expensive, unstable, or have substantial vapor pressure [4]. Comparisons for all investigated models for the two HTF molten salts will be facilitated in the context of the six operational modes to assess viability to a scaled 100 MW_e system.

3. Conclusions

A system layout for a 2-MW_{th} chloride molten-salt test loop is presented, including a thermodynamic system model developed using EES to model operational states during various operational modes. Two different chloride salt chemistries are compared to each other with respect to system efficiency. These operational modes consider six nominal operational modes, as well as two contingency scenarios that evaluate the employment of bypass lines with respect to process and instrumentation design (P&ID) diagrams. Pressure drops along major components are evaluated to calculate system TDH with corresponding system and pump curves. Preliminary results of this work have shown that higher system performance with respect to flow, by as much as 10% can be achieved under nominal steady operation with a ternary 20%NaCl/40%MgCl/40%KCl weight percent chloride salt composition, versus that of a 32%MgCl/68%KCl chloride salt composition.

4. References

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