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Operational Modes and System Design of a 2.0 MWth Sodium-Molten Salt Pilot System

Kenneth M. Armijo[1], Matthew D. Carlson[2], Dwight S. Dorsey[3], Jesus D. Ortega[2], Dimitri Madden[2], and Craig S. Turchi[4]

[1]Ph.D., Sandia National Laboratories, P.O. Box 5800, MS-1127, Albuquerque, NM 87185-1127, (505) 284-3425, kmarmij@sandia.gov
[2]Concentrating Solar Power Department 06123, Sandia National Laboratories, PO 5800 MS 1127, Albuquerque NM, 87185, USA.
[3]Bridgers and Paxton, 4600-C Montgomery Blvd NE, Albuquerque, NM 87109, USA.
[4]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA.

1. Introduction

The properties of sodium suggest that 90%-efficient concentrating solar power (CSP) receivers can be designed with existing technology [1] to improve overall thermodynamic system efficiencies. An alternative that uses salt storage with sodium as the receiver heat-transfer fluid is planned to leverage that fluid's ability to support higher flux limits on the receiver. Commercial sodium CSP plants have been previously proved for operation, using sodium as the heat transfer fluid for high-flux receivers, such as the 1.2 MW VAST solar facility [2]. Although high limits may be possible with higher-temperature molten salts, such as chlorides and carbonate, system challenges can persist with regard to corrosion and cost issues respectively. Therefore, to fully realize SunShot efficiency goals of \$15/kWh$_{th}$ HTFs and an LCOE of 6¢/kWh [3], more thermally efficient receivers, employing heat transfer fluids (HTF), such as sodium will be required. Liquid alkali metals are promising due to their high thermal conductivity, however less suitable as storage media due to lower heat capacity and higher material cost than molten salt alternatives [4]. High conductivity improves heat transfer and allows a receiver to operate at high solar heat flux, while maintaining an acceptable temperature difference between the absorber inner surface and the fluid [2]. High conductivity also alleviates thermal stress issues by reducing front-to-back receiver tube temperature difference [5], to achieve DOE Generation 3 system operational temperature goals of 720 °C [6]. The Gen 3 Liquid-Pathway team, comprised of various research institutions, and led by NREL, are developing a concentrating solar power (CSP) system to be developed to advance liquid-phase 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. This work is intended to advance CSP systems design with next-generation salt or alkali metal heat transfer fluid (HTF) capable of interfacing with a supercritical carbon dioxide (sCO2) Brayton cycle operating at 720 °C and ~50% efficiency. A system model design, Fig. 1, for a 2.0-MW$_{th}$ receiver test loop has been developed with a target receiver temperature of 750 °C, as well as hot and cold tank storage temperatures of 720 °C and 500 °C respectively.

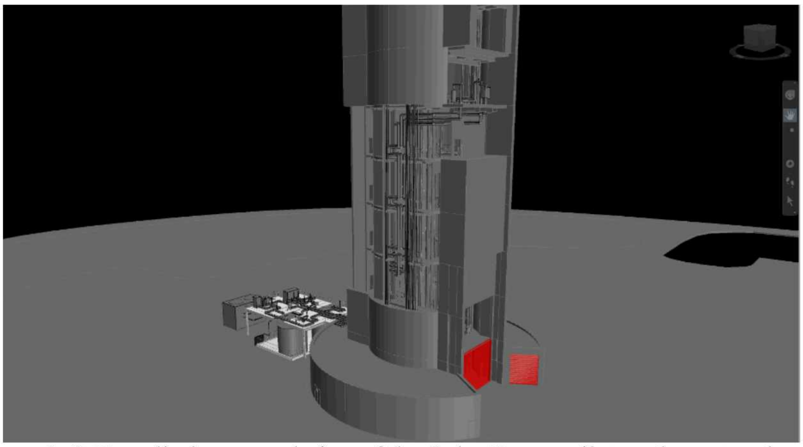

Figure 1. 3-D preliminary rendering of the Solar Tower pilot-scale system layout

The system design includes liquid sodium employed as an HTF for the receiver, riser and downcommer sections, where it transfers heat via a sodium-to-salt heat exchanger (HEX). The ternary chloride molten salt is used as the thermal energy storage (TES) media for 6 hours. To facilitate the designed storage duration and thermal heat input, the calculated mass flow rate of the sodium is 5.73 kg/s, which requires a 33,072-gallon salt TES inventory. To facilitate thermal transport between the receiver and the TES, a piping and flow control system has been designed to ensure a 1MW$_{th}$ heat input to a salt/sCO_2 heat exchanger that provides thermal input to an sCO_2 Brayton power cycle. Operational modes investigated include steady state operation, as well as transient start-up, shut-down and idle modes. In this work, engineering design has been performed for a Pilot-scale test system operated at Sandia National Laboratories. Comparison is made between this system and one using a chloride molten salt, with a

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20%NaCl/40%MgCl/40%KCl weight percent composition. This research also investigates performance for a scaled $100MW_{Net}$ system, employing sodium as the receiver HTF, operating under the same investigated operational modes.

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, and along both hot and cold legs of a pilot-scale plant. For this investigation, both steady-state and transient models were developed pertaining to respective operational modes of the thermal-hydraulic system. 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 faciliatate 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.

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 reciever, heat exchanger, downcommer 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 with a 2.5 in. inner diameter (ID), composed of schedule 80, Inconel 617 alloy for the hot leg, and SS347 for the cold leg. Heat losses along the respective flow-legs are evaluated with respect to total system efficiency.

A final analysis is conducted using the data generated from the pilot-system to assess a commercial-scale model to achieve the SunShot CSP levelized cost of electricity (LCOE) goal of 6¢/kWh [3]. For the TES, 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 models will be facilitated in the context of the six operational modes to assess viability to a scaled 100 MW_e (130 MWt_h) system, assuming a 30% efficiency, from the point of view of thermodynamics.

3. Conclusions

A rigorous thermodynamic system model is in development using EES to develop operational modes for a 2.0-MW_{th} sodium system test loop with a ternary chloride molten-salt TES. This work also investigates system performance and efficiency comparisons between the sodium system design, and one that flows a ternary chloride salt through a receiver, downcommer and riser sections. These operational modes consider six nominal operational modes, as well as two contingency scenarios that evaluates the employment of bypass lines with respect to process and instrumentation design (P&ID) diagrams. Pressure drops along major components evaluate calculated system TDH with corresponding system design and pump curves, with respect to a long-vertical shaft pump approach. Preliminary results of this work have been calculated with respect to flow with a cold pump TDH of 84.9 m under nominal steady operation, and a receiver temperature of 750 °C, with TES storage being provided by a ternary 20%NaCl/40%MgCl/40%KCl weight percent chloride salt composition. Further work is on-going to calculate system temperatures and pressures for 35 thermodynamic state points to assess thermal-fluid performance and reliability.

4. References

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