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Dynamic Modelling of a Concentrating Solar Thermal Plant with a Packed Bed Energy Storage

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Abstract. The Air-packed bed system is a cost-competitive concentrating solar thermal system that employs air as the heat transfer fluid and a solid packed bed as the thermal energy storage medium. The thermocline behavior of the packed bed plays an important role in the performance and operation of the system, so a dynamic model of the TES is needed to evaluate the design and performance of the system. A high-fidelity first-principle TES model is often too computationally expensive to incorporate into a larger system model for simulation and optimization at an annual time scale. Here, we develop in Modelica a system model for a CST concept plant with a reduced order TES model to ensure the necessary thermocline fidelity while maintaining suitable computational performance. The validity of the reduced order model is quantified both against simulation results from a first-principle finite-difference model and against real-world test data taken at the Heliogen Test Facility in Lancaster, CA. The thermocline fidelity and computational performance of the system model are then demonstrated with an annual simulation run of the concept air-packed bed plant.

Keywords: Modeling, Simulation, Modelica, Thermal Energy Storage, Packed Bed

1. Introduction

In the Concentrating Solar Thermal (CST) industry, the air has long been proposed as a heat transfer fluid to couple to a solid packed bed sensible heat Thermal Energy Storage (TES) for 24-7 steam production [1 - 3]. The temperature profile (or thermocline) of the packed bed storage plays an important role in the performance and operation of the system. As shown in Figure 1, during charging and discharging, the thermocline moves towards the cold end and hot end, respectively. The air temperature at the cold end rises near the end of the charging cycle; the air temperature at the hot end degrades near the end of the discharging cycle. Due to process constraints on temperatures, TES thermocline has significant implications on storage utilization and so the overall system performance.

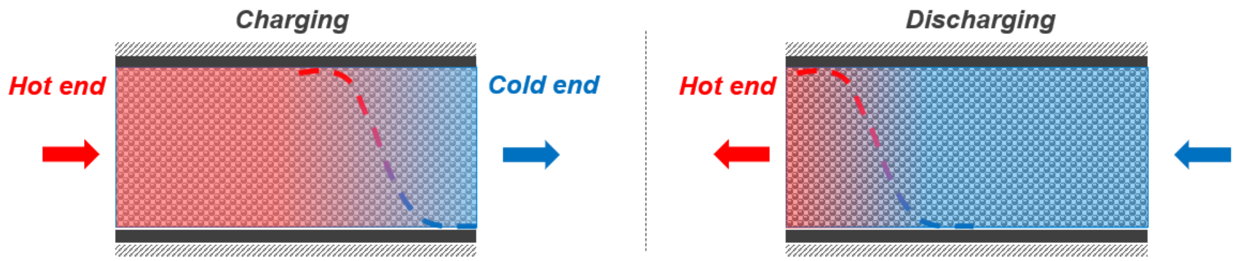

Figure 1. Thermocline of a sensible-heat packed bed thermal energy storage

There have been numerous studies on sensible-heat packed bed TES modeling to improve model fidelity and accuracy [4 and 5]; however, a high-fidelity model is often undesirable for system-level simulation running at an annual time scale due to its high computational cost. Moreover, optimizing a system design often requires many performance simulations to sweep a parameter space. A reduced order dynamic TES model is thus needed to achieve both adequate fidelity and low computational cost, and the tradeoff between model fidelity and computational cost needs to be quantified and assessed. This paper presents the development, validation, and demonstration of an air-packed bed system model with a reduced order TES model.

2. Model Development

2.1 Air-Packed Bed Plant Model with a Modelica Reduced Order TES Model

A system model of a steam-producing air-packed bed concept plant was developed in the Modelica language within Modelon Impact development environment. As shown in Figure 2, solar energy from the heliostat field is concentrated on the air receiver at the top of the tower. The heated air is then transported from the receiver to the ground level through a downcomer duct and split into two lines: the steam generator line to produce steam and the TES line for energy storage. Each line has a separate blower to control the flow rate. The cold air is returned to the receiver through a riser. When the system operates in discharge mode, the receiver is isolated by valves, and the air travels in the opposite direction through the TES, continuing to provide heat to the steam generator. A controller provides blower setpoints and specifies the plant operation scheme.

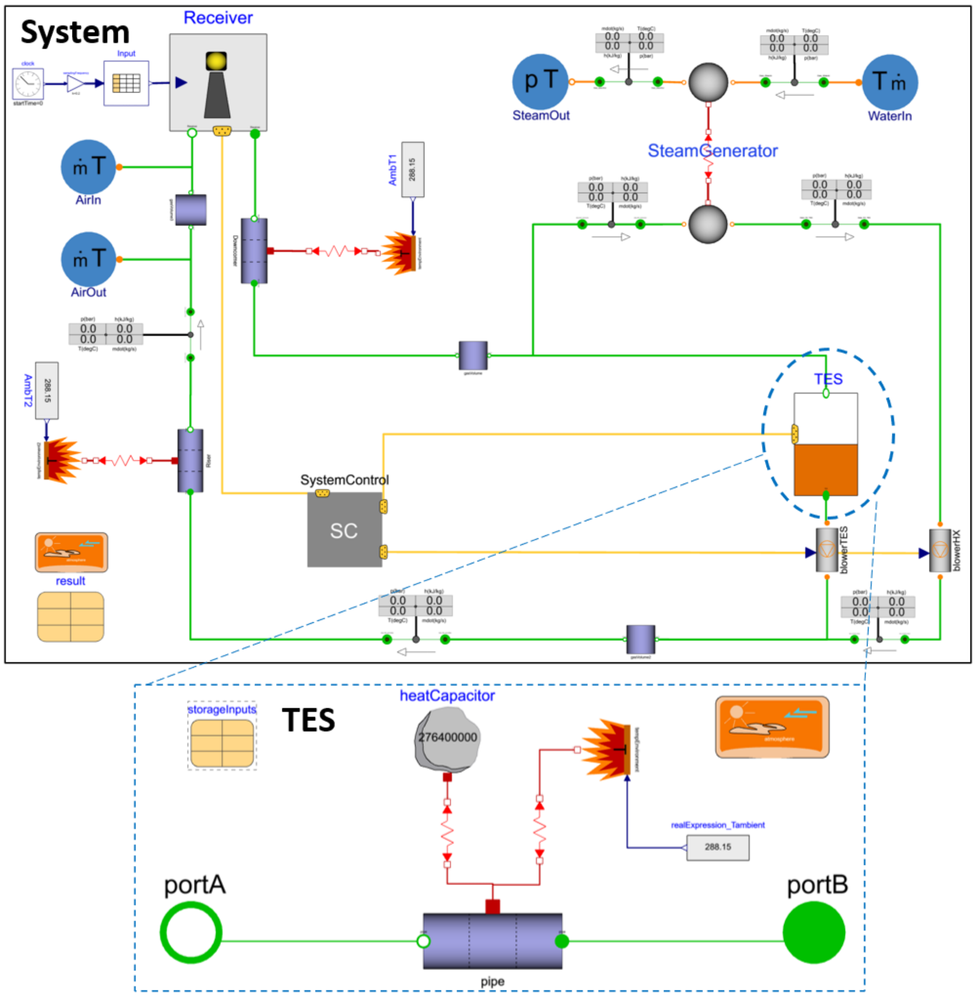

Figure 2. A System model of a CST plant with a reduced order TES model in Modelica

The TES is reduced order model (ROM). It is modeled as an axially discretized pipe, assuming no temperature variation in the radial direction. A heat capacitor is connected to each pipe node to mimic the packing material that stores sensible heat. The heat capacitor is a 0D energy sink, assuming lumped capacitance and uniform temperature profile within the storage material. This is valid when the packing diameter is small. The heat transfer coefficient between the air and packed bed and the heat loss coefficient for TES heat that loses to the ambient can be specified by the heat connectors. Although pressure across the system can be modeled in details in the Modelica model, hydraulic analysis is not part of the scope of this study. The Modelica model is wrapped into a functional mockup unit and executed in the Python environment for easier result analysis and optimization.

2.2 Finite-difference TES Model in MATLAB

To validate the ROM and understand the quantifiable tradeoff between accuracy and computational cost. A high-fidelity first-principle finite-difference model (FDM) model was developed in MATLAB as the reference. Shown in Figure 3, the FDM is a one-dimensional, two-temperature model governed by the heat and fluid equations (Equations 1 and 2), where ε is the porosity, ρ is the density, c_p is the heat capacity, T is the temperature, h_{fs} is the convective heat transfer coefficient, a_p is the packing surface area, $k_{eff,s}$ is the conduction heat transfer coefficient,

U_z is the velocity, h_{net} is the convective heat transfer coefficient to the ambient, and a_w is the wall surface area. Since the time constant of the fluid equation is about three orders of magnitude lower than the solid equation, the fluid equation is solved quasi-statically (setting the first term, $\partial T_f/\partial t$, to zero) except for when the Peclet number is less than 2 when the full transient equation is solved. The fluid flow is closed with a combination of the continuity equation and Ergun equation (Equation 3), where Δp is pressure drop, μ is dynamic viscosity, d is the diameter. In situations when the particulate media is not solid spheres, an appropriate modification to the Ergun equation is used [1]. This model was validated using experimental data found in literature from Hänchen et al. [6], and Klein et al [7] before being further analyzed versus the as-built system.

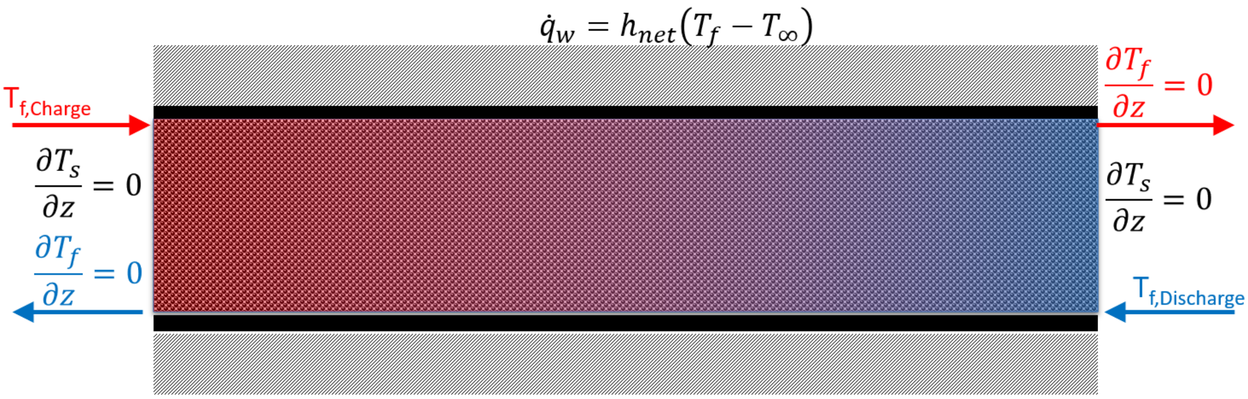

Figure 3. Schematic of heat flow in packed bed thermal storage model

Solid Heat Equation

$$(1-\varepsilon)\rho_s c_{p,s}\frac{\partial T_s}{\partial t} = h_{fs}a_p(T_f - T_s) + \nabla\cdot(k_{eff,s}\nabla T_s) \tag{1}$$

Fluid Heat Equation

$$\varepsilon\rho_f c_{p,f}\frac{\partial T_f}{\partial t} + \rho_f c_{p,f}U_z\frac{\partial T_f}{\partial z} = h_{fs}a_p(T_s - T_f) + \nabla\cdot(k_{eff,f}\nabla T_f) - h_{net}a_w(T_f - T_\infty) \tag{2}$$

Ergun Equation - Pressure drop equation

$$\frac{\Delta p}{L} = 150\frac{(1-\varepsilon)^2\mu_{gas}}{\varepsilon^3 d_{part}^2}U + 1.75\frac{(1-\varepsilon)\rho_{gas}}{\varepsilon^3 d_{part}}U^2 \tag{3}$$

3. Model Validation

3.1 Qualitative Examination of the Thermocline between the ROM and the FDM

To validate the ROM against the FDM, simulation was conducted according to a cold startup condition of the concept plant shown in Figure 2. The simulation conditions are listed in Table 1.

Table 1. Simulation condition for the air-packed bed concept plant

CST Concept Plant Configuration		
Hot end air temperature	°C / K	550 / 823
Cold end air temperature	°C / K	170 / 443
Initial TES temperature	°C / K	25 / 298
Packing material		Basalt
TES L / D		2

The temperature profile along the length of the TES generated from the ROM was compared to that of the FDM qualitatively in Figure 4. The result shows that the ROM can capture the key TES thermocline behavior qualitatively: as the TES is being charged, the thermocline moves from the hot end (axial position = 0 m) towards the cold end (axial position = 25m). Since the TES is initialized at the ambient temperature, the portion of the TES cold end remains at the ambient temperature at the end of the charging cycle. In the discharging cycle, the air flow at 170 °C heats up the cold end of the TES. Also, the air temperature at the hot end degrades as the discharging cycle progresses.

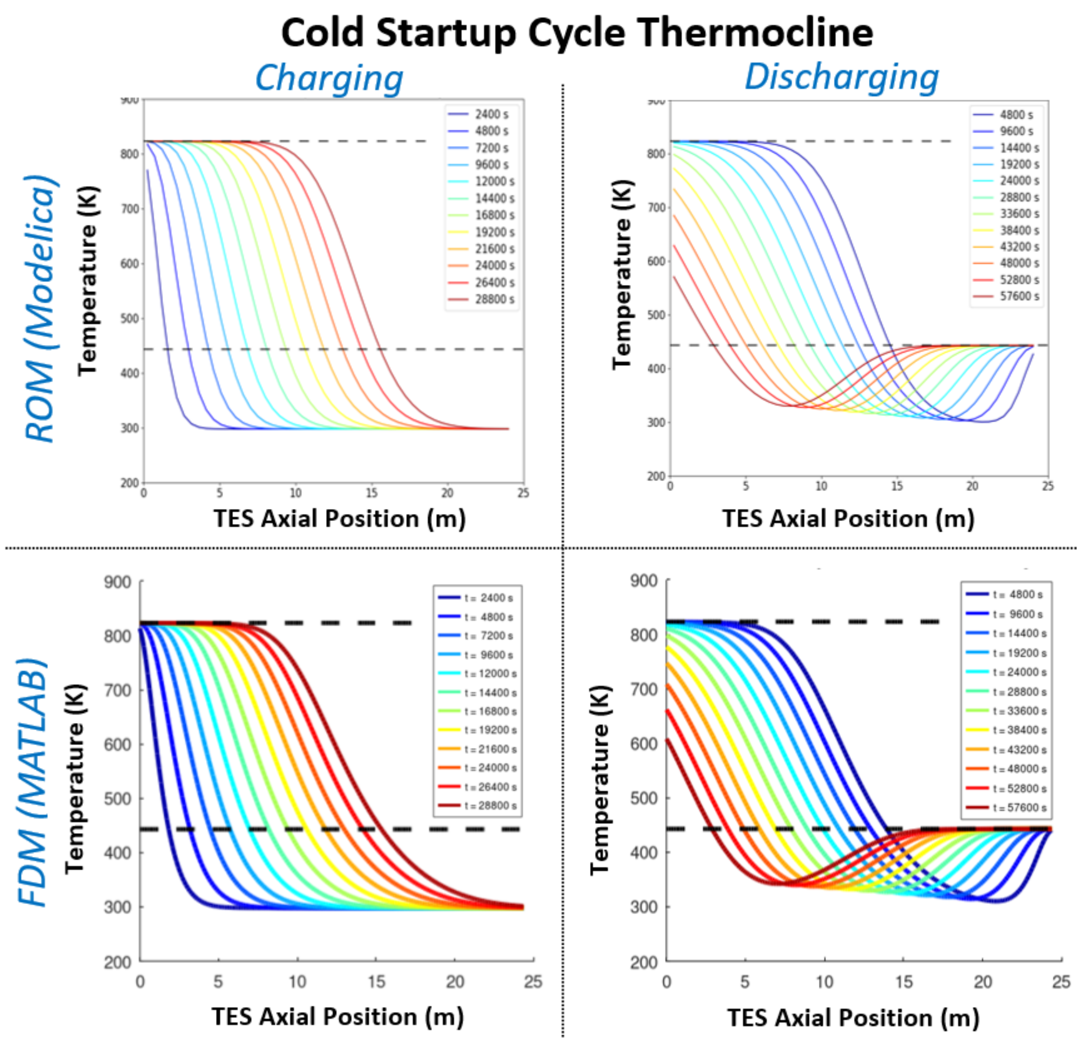

Figure 4. Simulated thermocline generated from the ROM and the FDM

3.2 Quantitative Assessment of the ROM with the FDM

To assess the performance of the ROM on both accuracy and computational performance, simulations were run for both the ROM and the FDM for three charging/discharging cycles with a duration of 72 hours at a 48 s simulation time interval. The simulation conditions are listed in Table 2.

Table 2. Simulation experimental conditions

TES Geometry		
TES diameter	m	0.914
TES length	m	3.657
Void fraction		0.45
Packing material		Basalt
Condition		
Charging time	hr	8
Discharging time	hr	16
# of cycle		3
Ambient Temperature	°C / K	25 / 298
Charging temperature	°C / K	550 / 823
Discharging temperature	°C / K	25 / 298
Charging air flow rate	kg/s	0.5
Discharging air flow rate	kg/s	0.25
Discretization (FDM / ROM)		200 / 10

The key parameters that impacts the ROM behavior, including the heat transfer coefficient between the air to the solid, the wall loss heat transfer coefficient, and the total storage heat capacity were calibrated to minimize the differences between the ROM and FDM outlet temperature predictions. Figure 5 shows the predicted temperatures at both the hot and cold ends of the TES predicted by the two models. The sum of the root-mean-square-error (RMSE) normalized to the charging and discharging temperature of the hot end and cold end air temperatures was used to quantify the difference between the two model results and yielded a normalized root-mean-square-error (NRMSE) of 3.6 %. The simulation time was reduced significantly by more than 400 times from 395 s of the high-fidelity model to 0.9 s of the reduced order model.

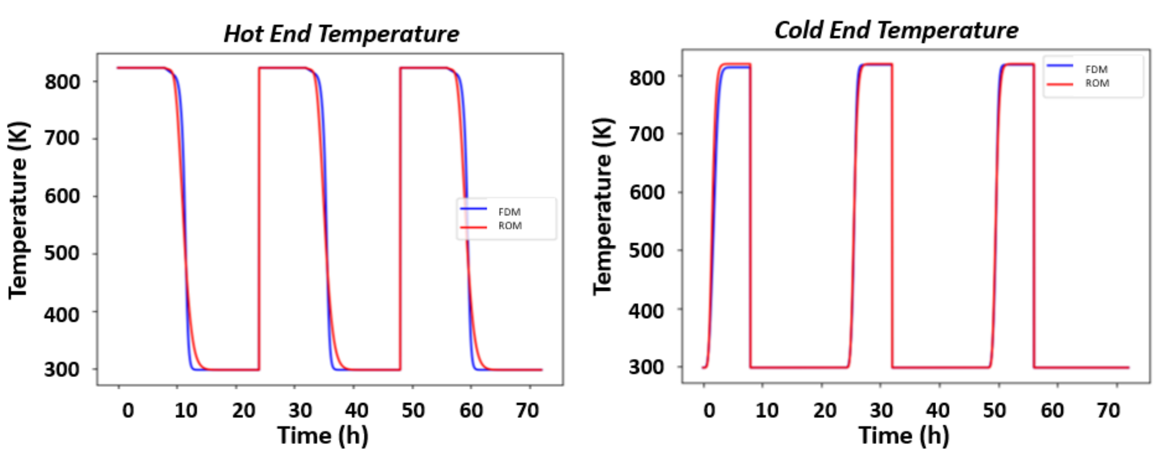

Figure 5. Simulation inlet and outlet temperature of the reduced order Modelica model and high-fidelity MATLAB model

3.3 Quantitative Assessment of the ROM with Real Testing Data

For validation, the TES ROM was also compared to data recorded in thermal testing at the Heliogen Test Site in Lancaster, CA. The Lancaster Test Site consists of a 400-kW heliostat field, an air receiver, and a TES, as shown in Figure 6. The TES is a vertical cylindrical packed bed 0.914 m in diameter and 3.657 m in length, filled with 1'' ceramic spheres as the packing material. Ten thermocouples were embedded in the length of the TES bed.

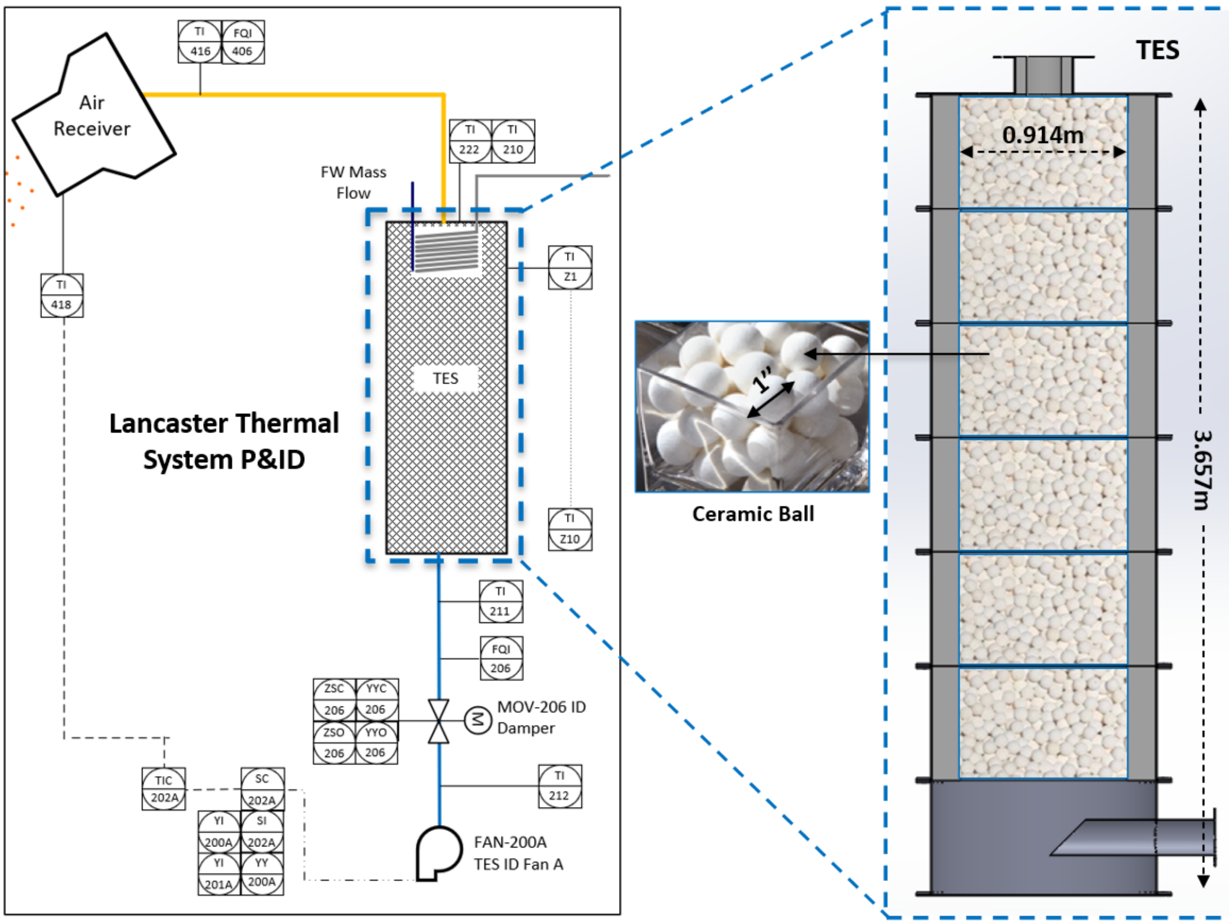

Figure 6. Lancaster testing facility P&ID and TES geometry

To validate the ROM with real measurement, the Lancaster TES was first charged for 6 hours and then discharged for about 10 hours, by drawing air into the TES from the receiver. The ROM was run with real measured TES inlet temperature, flow rate, and initial bed temperature conditions as inputs. Key parameters including the total heat capacity and heat transfer coefficients were calibrated to better represents the behavior of the physical TES. The predicted TES outlet temperature was then compared with the measured data, yielding 1.1 % NRMSE for the charging experiment and 4.6% NRMSE for the discharging experiment shown in Figure 7. The actual values are not presented to respect the confidentiality of the company data.

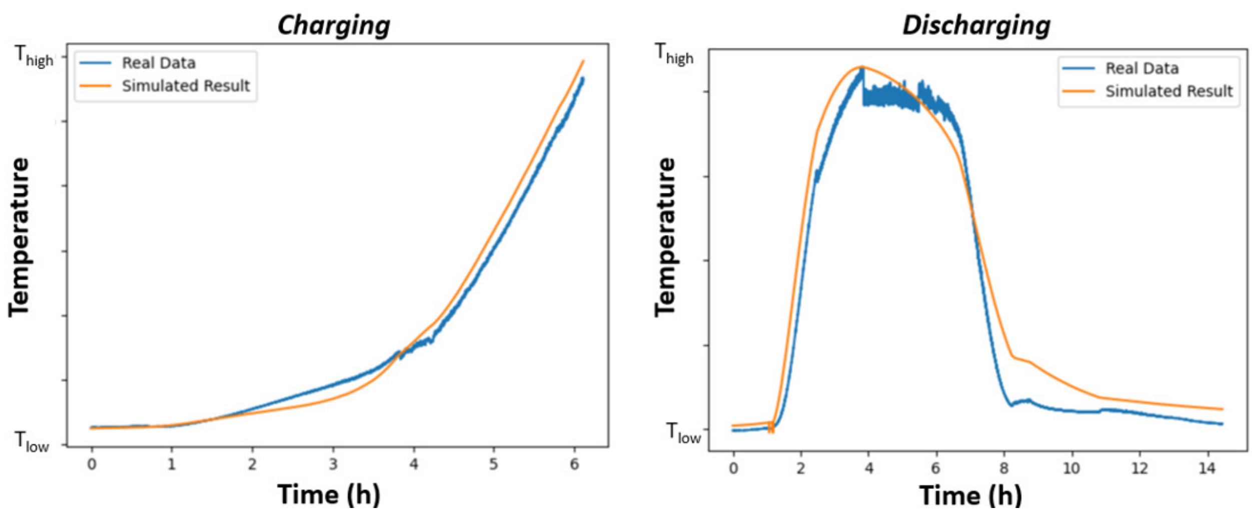

Figure 7. Comparison between real data and simulated result for thermal testing

4. Concept Plant Dynamic Simulation Demonstration

The reduced order TES model has been shown to capture the dynamic behavior of the TES well by comparing it with the high-fidelity FDM and real-world measurements. With computational speedup, the validated TES model was then used in the Modelica system model in Figure 2 to illustrate the effect of thermocline on the performance of the commercial-scale concept CST plant operating at the conditions shown in Table 1.

Figure 8 below shows a weekly sample of an annual system simulation, depicting the steam generator air flow rate and the TES charge fraction. The performance of the CST plant was simulated under two scenarios: the TES cold end temperature during charging is a) not limited (in another word, limited to the same charging temperature of 550 °C), and b) limited to 360 °C. This describes a situation where one needs to determine whether it is more economical to procure an expensive high-temperature blower that allows the thermocline to break through during charging or a cheaper carbon steel blower that typically only operates below 400 °C.

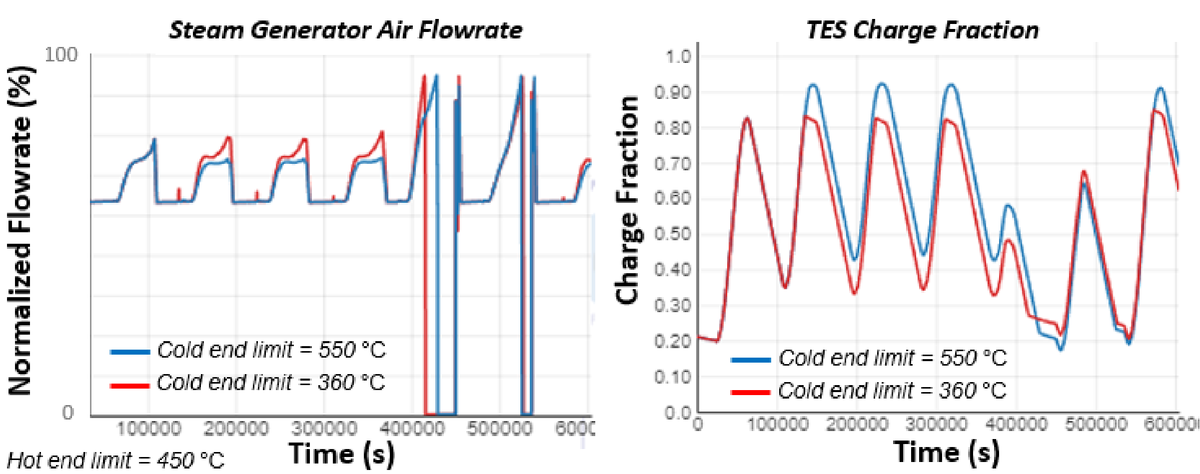

Figure 8. Predicted TES charge fraction and steam generator air flow rate with and without TES cold end temperature constraint

The result shows that due to the thermocline temperature variation, the air flow rate also varies to maintain the same level of heat output and steam production rate. This will affect the thermal performance of the steam generator and blower power consumption. With a cheaper blower and a temperature limit of 360 °C imposed, the TES is less utilized, leading to an earlier TES depletion, a longer plant shutdown, and so a lower capacity factor. While capturing the effect of thermocline on the system performance, the model also demonstrated adequate computational performance by completing an annual simulation in about 3 minutes.

5. Conclusion

Modeling the thermocline behavior of the TES in an air-packed bed CST plant is critical to evaluate the operation and the overall performance of the plant. It is, therefore, necessary that a system model include a dynamic TES model. Here, an air-packed bed CST system with a ROM was developed in Modelica to ensure both model fidelity and computational performance. The fidelity of the ROM was quantified by comparing the simulation result to that of an FDM in MATLAB and real testing data from the Heliogen Test Facility. The system model with a ROM TES was demonstrated to capture the TES thermocline behavior as well as adequate computational performance.

The development of the system model and reduced-order TES model can be used to assist in a CST plant design and optimization. The validation pipeline also allows further model tuning as new knowledge/data become available and quantitative balancing between fidelity and computational performance depending on simulation objectives.

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Data availability statement

The data used in this study is considered proprietary information of Heliogen Inc. Access to the data can be granted upon request and approval from the appropriate authorities within Heliogen.

Author contributions

Eric Jin: Writing – original draft, Conceptualization, Investigation, Formal Analysis

Andrew Oles: Methodology, Writing – review & editing

Katie Harding: Data Curation, Formal Analysis

Nate Thomas: Supervision, Writing – review & editing

Competing interests

The authors declare no competing interest

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