ANNUAL PERFORMANCE CHARACTERIZATION OF A GEN3 PARTICLE-BASED CONCENTRATING SOLAR PLANT WITH A SPATIALLY RESOLVED TRANSIENT THERMAL STORAGE MODEL

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Introduction: Particle-based Gen3 CSP plants are being designed to provide reliable grid-wide power supply

Target Performance:

- $\geq 1\,\text{MW}_{th}$ Duty
- 6 hrs of full capacity storage
- Total temperature drop $\leq 50 \, ^\circ\text{C}$
- sCO2 HX Outlet temperature $\sim 700 \, ^\circ\text{C}$

Introduction: The transient thermal characterization of particle-based components is necessary for system integration.

Discharging Hot TES Bin

Transient and spatially resolved temperature profile in TES bin to capture the transient outlet temperature [2]

Particle-to-sCO$_2$ Heat Exchanger

Particle-tosCO$_2$ heat exchanger designed for the Gen3 Particle Pilot Plant (G3P3) [3]

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Introduction: CSP cycles are particularly sensitive to thermal transients because of local DNI fluctuations.
Research Question and Engineering Objective

• Q: What is the characterized impact of transients occurring from solar intermittency and component-level heat loss on system capacity/performance?
  • General Hypothesis: non-negligible
• Objective: Develop a model that can simulate fast dynamics in components (<10 s) for characterizing performance and developing mitigating controls.
Our transient system model includes an integrated receiver, storage bin, and heat exchanger to capture the passive impact of this intermittency.
Falling Particle Receiver Model

\[ V_r \rho_s c_{p,s} \Phi_s \frac{dT_s}{dt} = \alpha_s Q_S - A_r \sigma \varepsilon_s (T_s^4 - T_\infty^4) - A_r h_\infty (T_s - T_\infty) + \dot{m}_s c_{p,s} (T_s - T_{s,in}) \]

Fast transients/energy storage
Absorbed solar irradiation
Convective losses
Advection/mass transport

\[ T_s(t = 0) = 600 ^\circ C, \quad T_s(x = 0) = 600 ^\circ C \]

Major assumptions (meant to make the model conservative):
- Falling curtain emits diffuse radiation as a gray body to ambient surroundings, neglecting effects of the FPR enclosure.
- Entering particles are heated instantaneously upon entering the exposed aperture and the residence time is very low (lumped approximation)
Particle Thermal Energy Storage Model

\[ T_0 = 800 \, ^\circ C \quad T_0 = 775 \, ^\circ C \quad T_0 = 763 \, ^\circ C \]


Particle-to-sCO₂ Heat Exchanger Model

\[
\rho_s c_p s \phi_s V_s \left( \frac{\partial T_s}{\partial t} + v_s \frac{\partial T_s}{\partial x} \right) = 2h_s A_s (T_m - T_s) \\
\rho_{CO₂} c_{p,CO₂} V_{CO₂} \left( \frac{\partial T_{CO₂}}{\partial t} + v_{CO₂} \frac{\partial T_{CO₂}}{\partial x} \right) = 2h_{CO₂} A_s (T_m - T_{CO₂}) \\
\rho_m c_m V_m \frac{\partial T_m}{\partial t} = h_s A_s (T_s - T_m) - h_{CO₂} A_s (T_m - T_{CO₂})
\]

(Particle Energy Equation)
(sCO₂ Energy Equation)
(Stainless Steel Energy Equation)

![Diagram showing Particle Inlet and sCO₂ Inlet](image-url)
Integrated Model Simulation for Summer in ABQ, NM

- All components have prescribed inlet/outlet mass flow rates
  - Contrary to implementing temperature controls
- Components begin at ambient temperature (cold start)
  - Thermal shock/ramp rate limits not considered
- Particles enter the receiver at 600 °C
- sCO$_2$ enters the heat exchanger at 550 °C
- TMY3 DNI data from June 21 – June 28
Integrated Model Simulation for Summer in ABQ, NM

Solar Input from Heliostat Field

Receiver Outlet Temperature

TES Bulk Volumetric Temperature vs. TES Outlet Temperature

HX Particle Inlet Temperature vs. HX sCO₂ Outlet Temperature
Conclusions/Take Away Points

• Thermal controllers using mass flow valve actuators, especially at the receiver, is a key part of maintaining steady operation (considering trade-offs).
  • But the overall fluctuation in DNI must be made up from somewhere else to maintain capacity.
• System transients not only from solar intermittency, but also heat attenuation in components needs mitigation.
• The ability to capture dynamics on the order of ~10 seconds in a system model will enable the development of proactive operational and supervisory control algorithms.
Future Developments: Implementing Compensatory Controls
Thank You

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Aim 1: Particle domains and boundary conditions can be identified based on known kinematic behavior

\[ T(r, z) \]

\[ u(t) \]

\[ q_{rad}^{''} \]

(Radiation Exchange w/ Bin)

\[ q_{BC1}^{''} \]

(Exchange w/ top flow surface)

\[ q_{conv}^{''} \]

(Free Surface Losses)

(Advection in top flow channel)

\[ q_{BC3}^{''} \]

(Exchange w/ center channel)

(Advection in center flow channel)

\[ q_{base}^{''} \]

(Base Losses & Energy Storage)

\[ q_{conv}^{''} \]

(Wall Losses & Energy Storage)
Aim 1: Geometric and velocity field simplifications provide an elegant derivation framework

\[ \frac{DT}{Dt} = \alpha \nabla^2 T \]

Top Flow Surface

Center Flow Channel

\[ \frac{\partial T}{\partial t} = \alpha \nabla^2 T \] (Heat Kernel)

Stagnant Particle Region

\[ G(r, z, t | r', z', t') \]

Effect of unit impulse at location \((r', z')\) released at time \(t = t'\)

\[ G(\text{effect} | \text{impulse}) \]

Contribution from IC, \(\rho(r, z)\)

\[ T(r, z, t) = \int_S G_{ff}(r, z, t | r', z', \tau) \bigg|_{\tau=0} \rho(r', z') \, dA' + \Omega_1(r, z, t) + \Omega_2(r, z, t) + \Omega_3(r, z, t) + \Omega_4(r, z, t) \]

\(\Omega_n(r, z, t): \) Effect of \(BC_n\) on temperature at \((r, z, t)\)
Aim 1: Neglecting the energy storage in the bin material, we can already see that the salient physics are captured.

Hold Time: 450 s
\[ \dot{m}_{out} = 0.045 \text{ kg/s} \]

Hold Time: 900 s
\[ \dot{m}_{out} = 0.041 \text{ kg/s} \]

Hold Time: 1800 s
\[ \dot{m}_{out} = 0.038 \text{ kg/s} \]

Experimental verification results with small bin testing performed at Sandia National Laboratories by Jeremy Sment that was first presented at Solar PACES 2020 [12, 13].


Aim 1: The same procedure can be generalized to be utilized for the charging, holding, and discharging storage modes

General Heat Kernel Solution from Homogeneous Auxiliary Problem

\[ G(z, r, Fo | z', r', \mathcal{F}) = \sum_{n} \sum_{m} C_{nm} X_{n}(z, \beta_{n}) X_{n}(z', \beta_{n}) X_{m}(r, \eta_{m}) X_{m}(r', \eta_{m}) F(Fo - \mathcal{F}, \lambda_{nm}) \]

General Temperature Solution:

- Stagnant Particle Domain
  \[ A_{n} \frac{\partial \theta}{\partial z} \bigg|_{z=z_{0}} + B_{1} \theta \bigg|_{z=z_{2}} = f_{1}(r, Fo, \theta) \]
  \[ -A_{3} \frac{\partial \theta}{\partial r} \bigg|_{r=r_{0}} + B_{3} \theta \bigg|_{r=r_{0}} = f_{3}(z, Fo, \theta) \]

- \[ \frac{\partial \theta}{\partial z} = \nabla^{2} \theta \]
  \[ A_{4} \frac{\partial \theta}{\partial r} \bigg|_{r=b} + B_{4} \theta \bigg|_{r=b} = f_{4}(z, Fo, \theta) \]

- \[ -A_{2} \frac{\partial \theta}{\partial z} \bigg|_{z=z_{0}} + B_{2} \theta \bigg|_{z=z_{0}} = f_{2}(r, Fo, \theta) \]

Green's formula used to account for spatially resolved and transient boundaries

Simulation Framework

sine/cosine Bessel functions exponential decay
Aim 1: With the simulation framework, boundary domains are solved for as if the particle temperatures are known.

Mass & Energy Transfer

\[ T(r) = T_{\text{stagnant}} \]

Flow Regions are Solved Semi-Discretely

\[
\frac{DT}{Dt} = \nabla^2 T
\]

\[
\frac{\partial T}{\partial t} = AT + b
\]

Solve linear system w/ constant input

\[ T = e^{At} T_0 \]

Wall & Base are Solved with a 1D Thermal RC Model

Example unit step response for G3P3 wall

\[ \tau_1 = 4.67 \text{ hours} \]

\[ \theta_1, \theta_2 \]

\[ \theta_3, \theta_4 \]

Particle Outlet

\( u(r) \)
Aim 1: In addition to predicting the outlet temperature, we can investigate the scaling of thermal storage bins

Consider the lumped bin approximation:

$$\theta(Fo) = \left(\theta_0 - \frac{Bi_t}{Bi} \theta_i\right) e^{-\frac{Bi}{Fo}T} + \frac{Bi_t}{Bi} \theta_i$$

$$\theta \equiv T - T_\infty, \theta_i \equiv T_i - T_\infty$$

$$Fo \equiv \frac{\alpha t}{H^2}, Bi \equiv \frac{\bar{U}H}{k}, Bi_t \equiv \frac{h_tH}{k}$$

If we look at the geometric scaling from a prototype, $[\cdot]_p$, to a commercial bin, $[\cdot]_c$, by a factor of $f$:

$$Bi_c = fBi_p, Bi_{t,c} = fBi_{t,p}, Fo_c = Fo_p/f^2$$

$$\theta_c(Fo) = \theta_p(Fo/f)$$
Aim 1: Similar scaling results are obtained by simulating scaled bins with the spatially resolved heat kernel model.

Prototype (H = 7m) and Commercial (H = 40m)
Aim 2: System analysis results

HX Effectiveness

$\epsilon \approx 0.75$

$\overline{\eta}_{l,max} = 52.5\%$

$\eta_l = 48.5\%$

$$\eta_l = \frac{m(h_{out} - h_{in})_{CO_2}}{\dot{Q}_{sol} + \dot{Q}_h}$$