This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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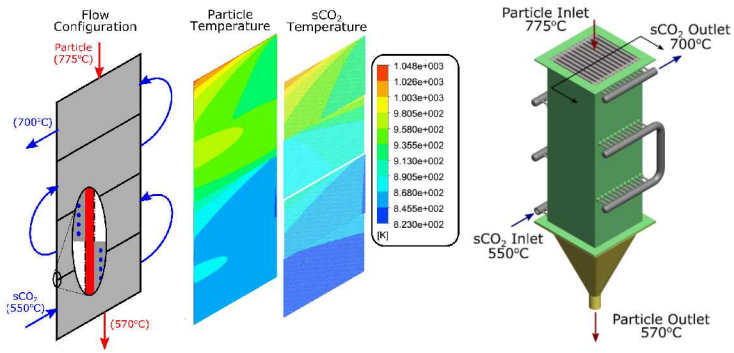

Transient Simulation of a 1MWth Test Bed of an Integrated Particle-Based CSP Plant Driving an sCO_2 Flow Loop

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Sandia National Laboratories, Concentrating Solar Technologies (8823)

PowerEnergy2018-7144, SAND2018-####

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Outline

- Introduction/Objectives
- Process Flow Model
- Transient Simulations and Control
- Conclusion/Future Work

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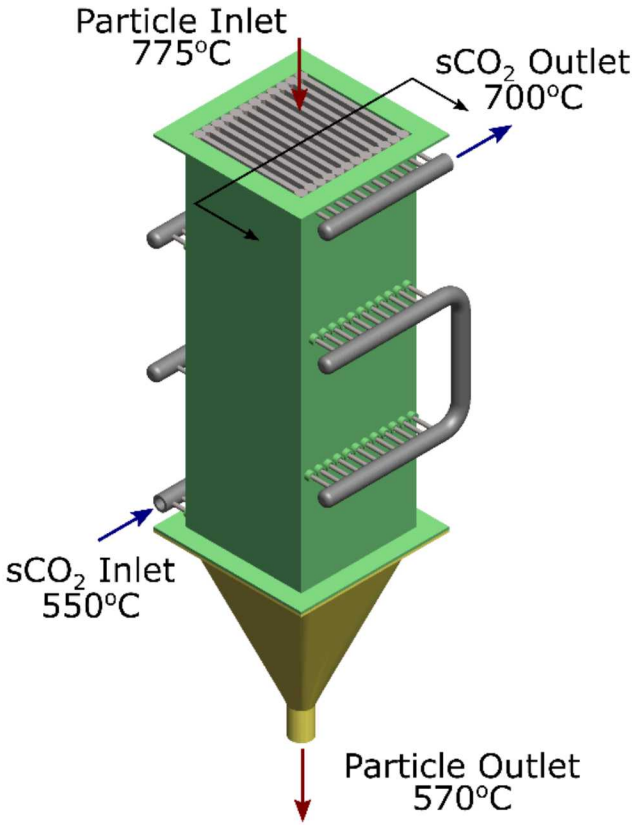
Particle receiver development has led to the need for an sCO_2-to-particle heat exchanger

- Particle-based CSP plants enable the use of sCO_2 power cycles
- Multiple particle receivers have been demonstrated at the megawatt scale
- Minimal work has been conducted on particle-to-sCO_2 heat exchangers



Objective

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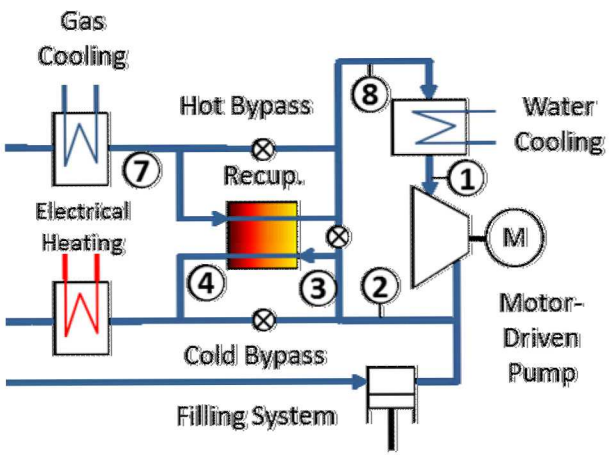
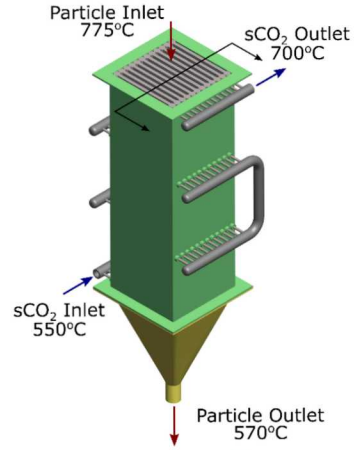
Falling Particle Receiver

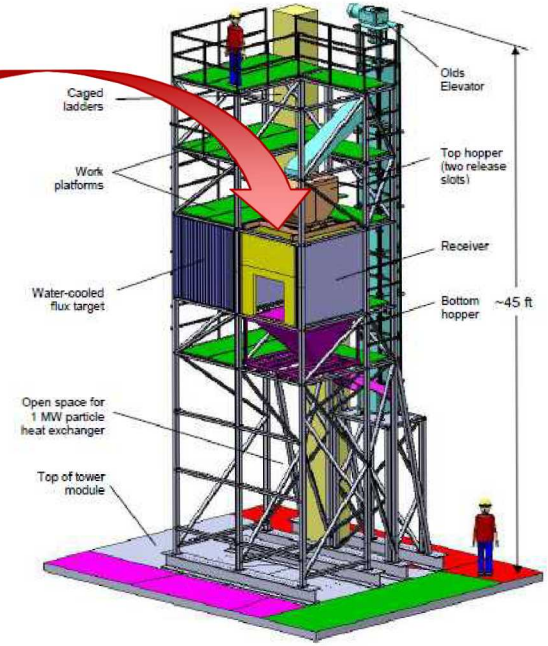
Particle/sCO_2 Heat Exchanger

sCO_2 Flow Loop



Carlson (2016)



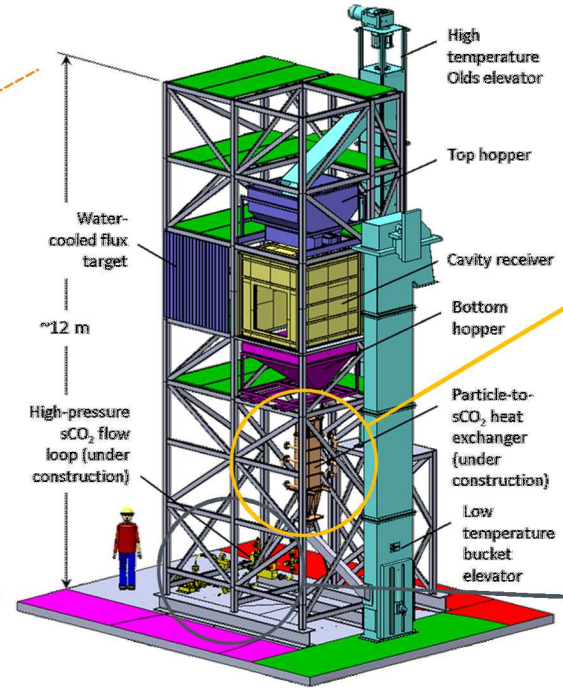


Ho and Christian (2016)

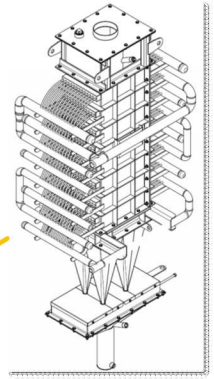
- Develop and test 100kW$_{th}$ prototype particle-to-sCO_2 heat exchanger

100 kW_t heat exchanger and sCO2 flow loop integrated with falling particle receiver module

Particle receiver testing at the National Solar Thermal Test Facility at Sandia National Laboratories, Albuquerque, NM

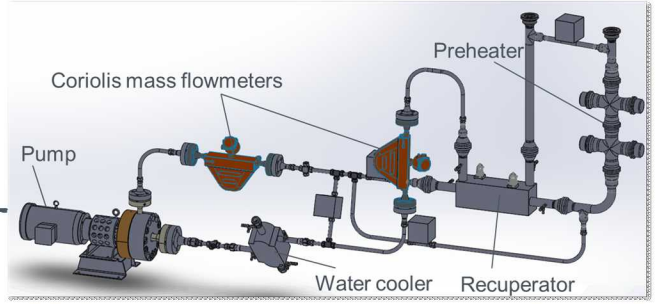


High-Temperature Particle Receiver



Solex/VPE particle/sCO2 shell-and-plate heat exchanger

- Heat duty = 100 kW
- $T_{particle,in}$ = 775 °C
- $T_{particle,out}$ = 570 °C
- $T_{sCO2,in}$ = 550 °C
- $T_{sCO2,out}$ = 700 °C
- $\dot{m}$ = 0.5 kg/s



sCO_2 flow system provides pressurized sCO_2 at 550 °C to heat exchanger for test and evaluation

- Demonstrate the operation of an integrated particle-driven sCO_2 cycle

Items of concern for integrated system operation

- The lack of a second storage bin presents unique control challenges not present in a real system
- Design point of the receiver (1 MW_t) is much greater than the design point of the heat exchanger (100 kW_t)
- Mass flow rate of receiver must be greater than the heat exchanger at all times
  - Minimum receiver flow rate is 0.5 kg/s
  - Maximum heat exchanger flow rates is 0.5 kg/s
- Solar thermal input must be reduced once particles in the hopper have reached 570°C
  - Heliostats will have to be removed to maintain receiver outlet (heat exchanger inlet) temperature of 775°C

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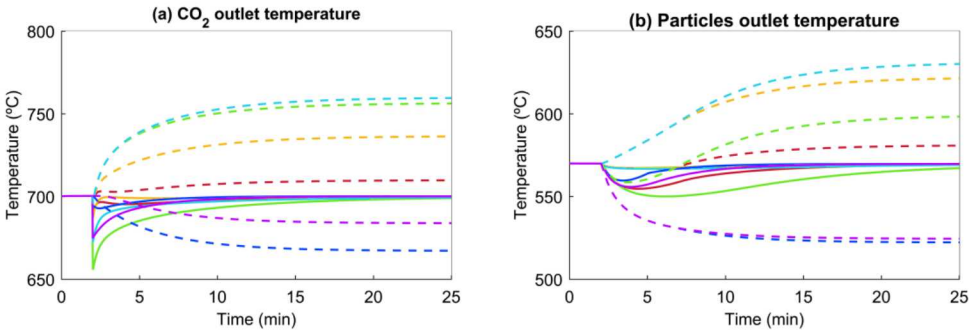
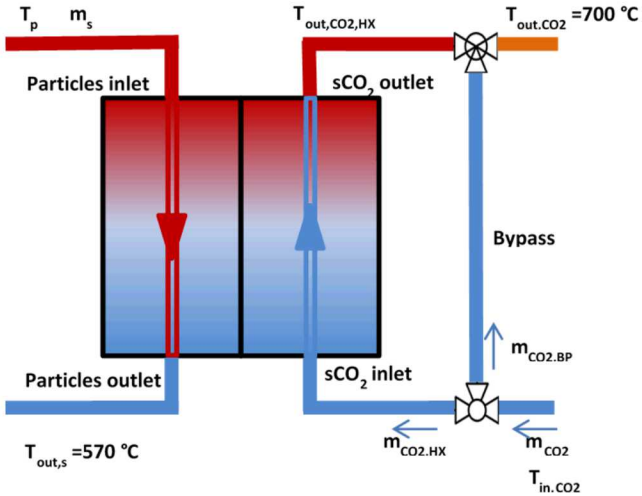
Prior work on transient modeling work of the particle-to-sCO_2 heat exchanger

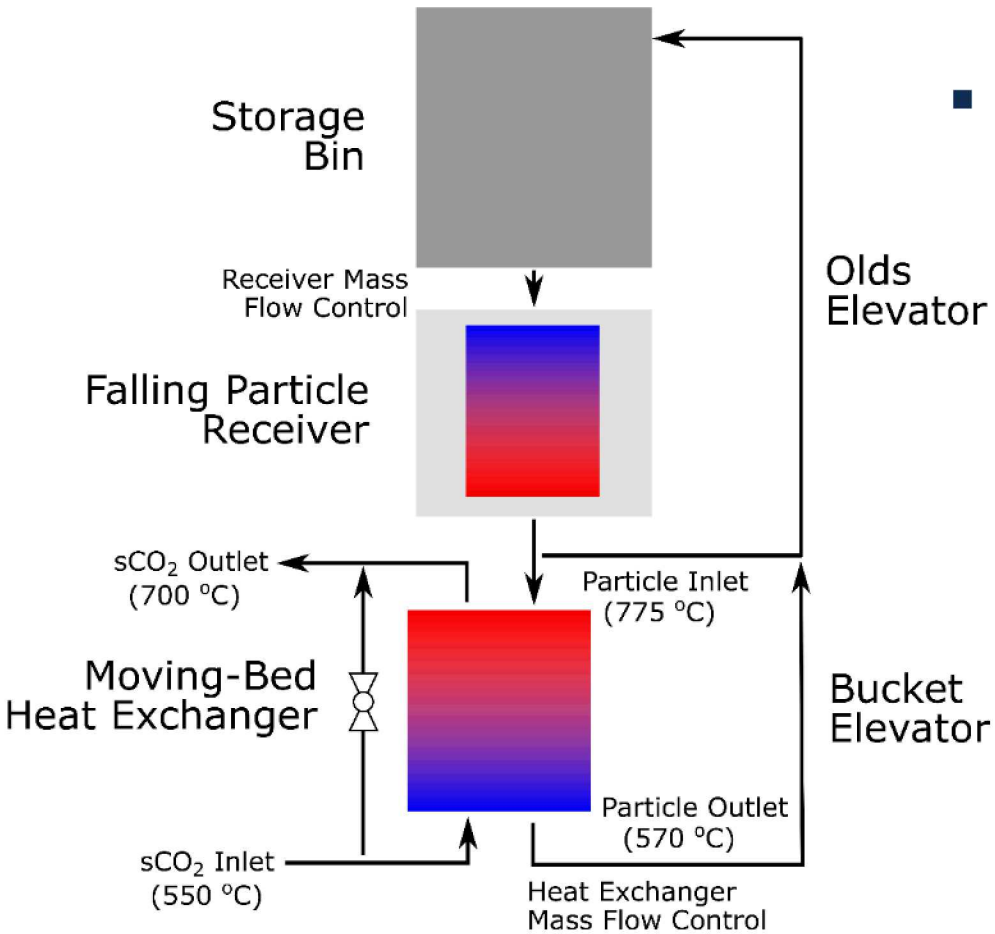
- Last year Sandia developed a transient model of the moving packed-bed heat exchanger for studying control and dynamic dispatch
- This work was documented in a journal publication which was published in *Applied Energy*





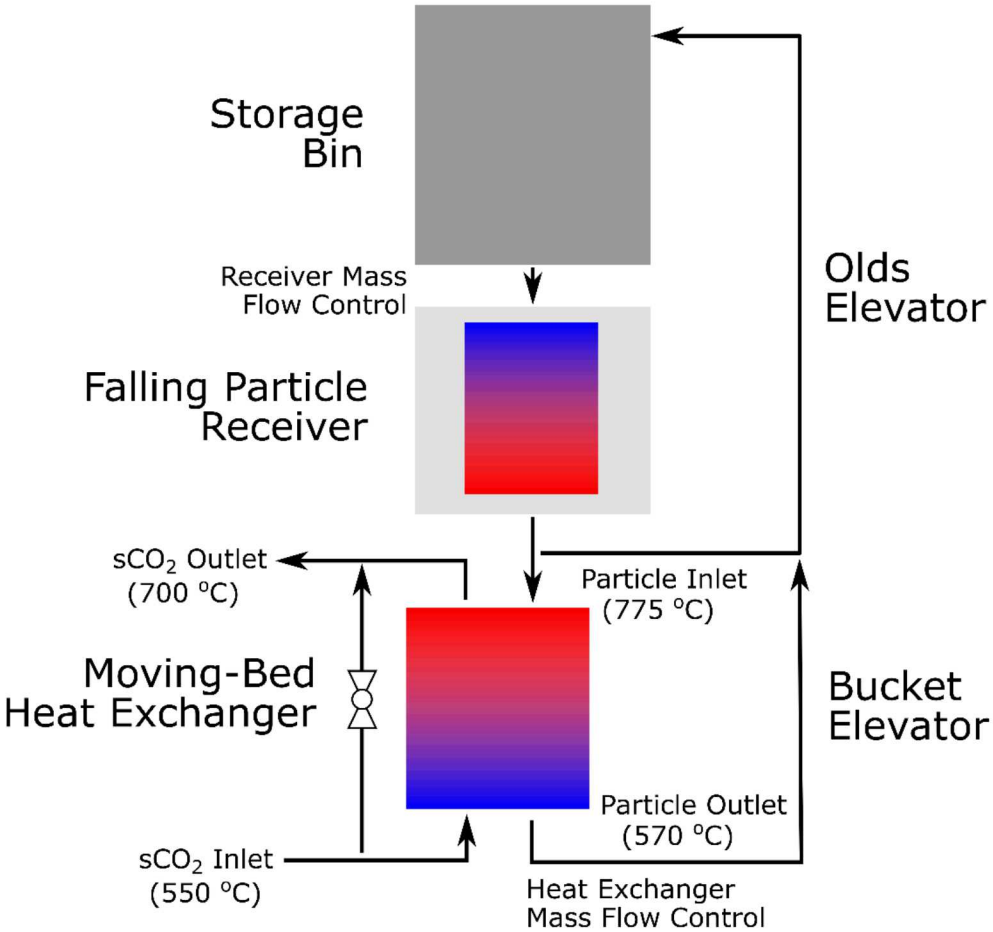
- The work was extended to incorporate all of the particle-based CSP system components

Process flow diagram of the integrated falling particle receiver and heat exchanger



- Model the startup and control of the fully integrated system:
  - Incorporate the transient particle heat exchanger into a system model
  - Develop additional models for the storage bin and particle receiver
  - Capture the effect of particle recirculation on the system transient

Component model development



Storage Bin Temperature Distribution

$$\rho_s \phi_s c_{p,s} \frac{\partial T_s}{\partial t} = -\rho_s \phi_s v_s c_{p,s} \frac{\partial T_s}{\partial x} + \frac{\partial}{\partial x}\left(k_s^{\text{eff}} \frac{\partial T_s}{\partial x} \right) - q''_{\text{loss}}$$

Solar Receiver Energy Balance

$$\eta_{\text{th}} q''_{\text{solar}} A_{\text{ap}} = \dot{m}_s c_{p,s} \left(T_{s,\text{out}} - T_{s,\text{in}} \right)$$

Heat Exchanger Temperature Distributions

$$\rho_s \phi_s c_{p,s} \frac{\partial T_s}{\partial t} = -\rho_s \phi_s v_s c_{p,s} \frac{\partial T_s}{\partial x} + \frac{2h_{sw}}{th_s}\left(T_m - T_s \right)$$

$$\rho_g c_{p,g} \frac{\partial T_g}{\partial t} = -\frac{\partial \rho_g v_g h_g}{\partial x} + \frac{2h_{gw}}{th_g}\left(T_m - T_g \right)$$

$$\rho_m c_{p,m} \frac{\partial T_m}{\partial t} = \frac{\partial}{\partial x}\left(k_m \frac{\partial T_m}{\partial x} \right) + \frac{2}{t_m}\left[h_{sw}\left(T_s - T_m \right) + h_{gw}\left(T_g - T_m \right) \right]$$

- The models were developed in MATLAB and solved using internal ODE integration tools

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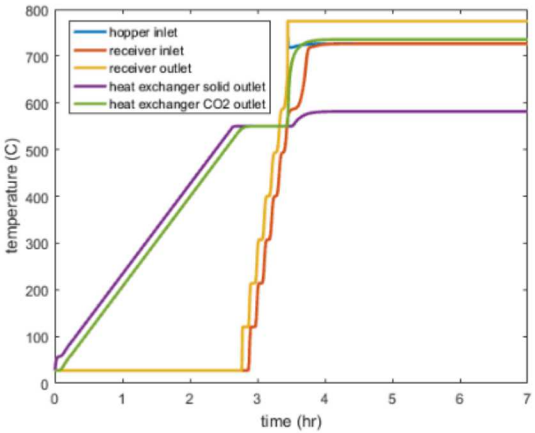
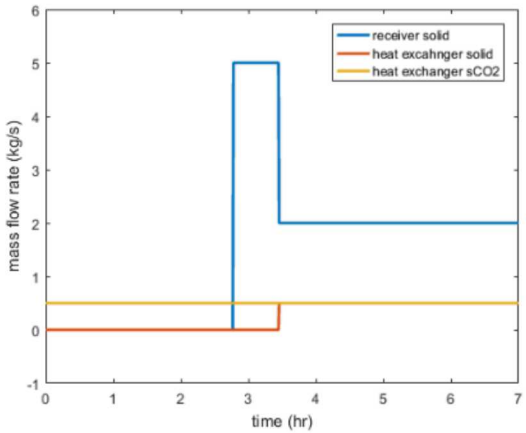
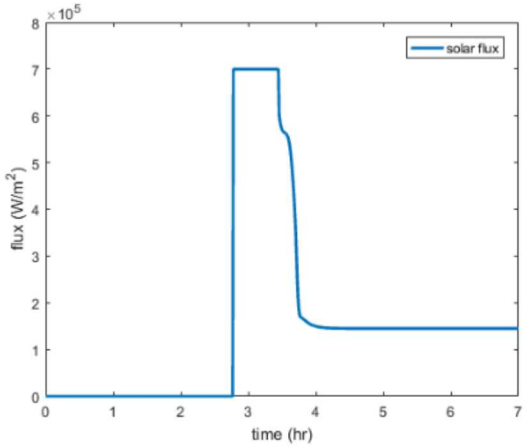
Simulation of the startup of the integrated system

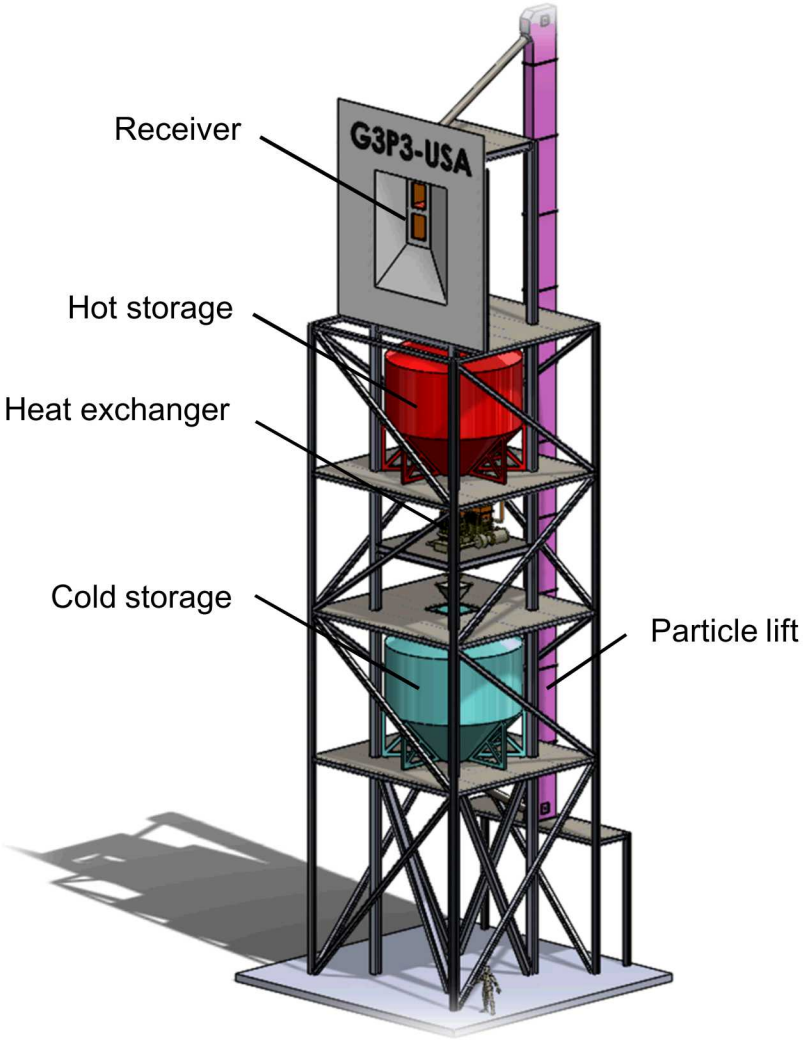






- Simulated the startup and operation of the integrated system form 25°C isothermal condition
- Initial period for preheating the heat exchanger to 550°C using the sCO_2 heater to reduce temperature gradients experienced during transients
- Receiver is used to preheat the particles in the system to a temperature of 700°C at constant flow rate (5 kg/s) and solar flux (700 kW/m^2)
- After preheating the particles, mass flow rate of the particles is turned down and heliostats are removed to maintain the system at particle inlet temperature of 775°C

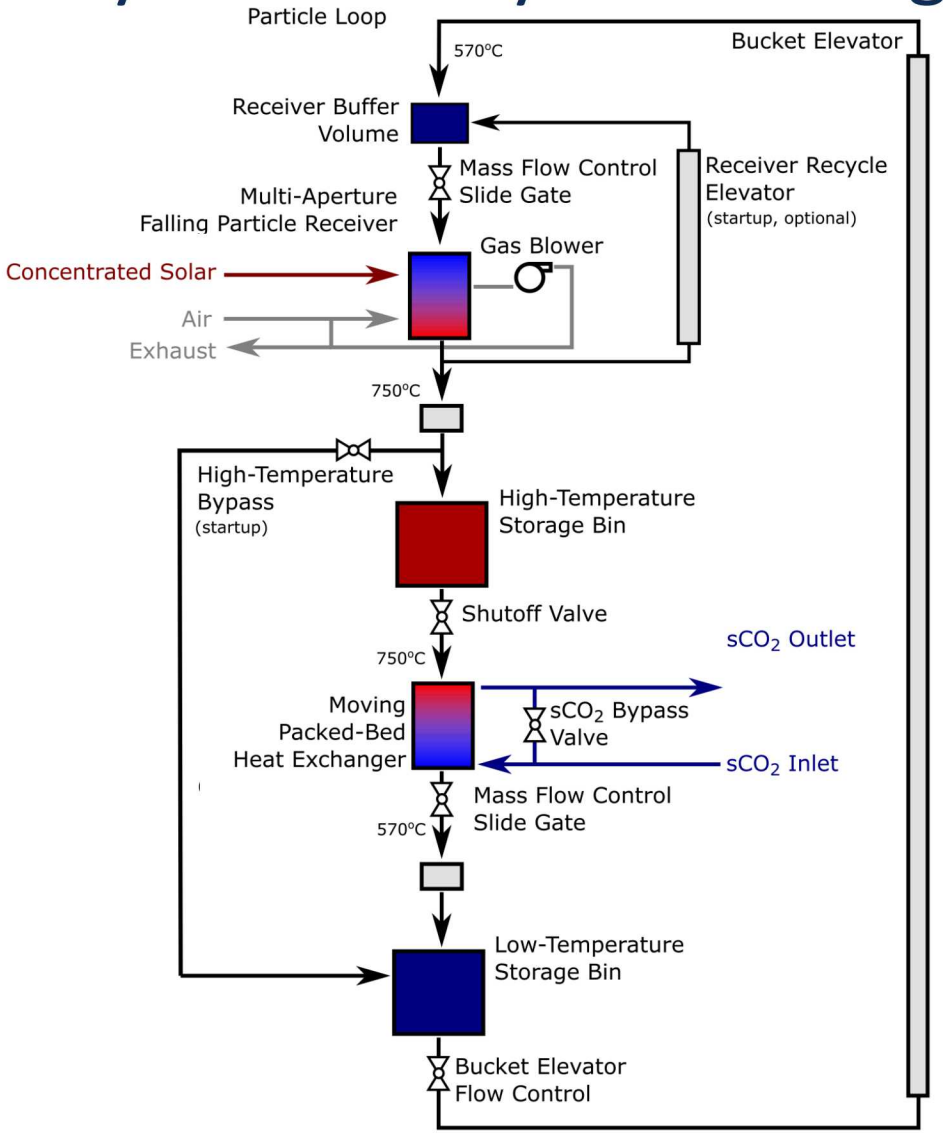
Control of Commercially Relevant Systems



Proposed G3P3 System

- Decoupled operation of falling particle receiver and heat exchanger
- Startup of the heat exchanger without temperature ramping from solar energy
- Startup of the solar thermal receiver and maintaining constant outlet temperature

Potential process flow diagram for a commercially relevant system configuration



Conclusion

- Process flow models of particle-based CSP system components developed an implemented for existing test loop
- Integrated control demonstrated for 1 MW_{th} test through heating with the particle receiver and sCO_2 flow loop
- Evaluated considerations for the operation of commercial system configurations

- Future work:
  - Simulate configurations that are representative of commercial systems
  - Heat exchanger 100 kW prototype will be commissioned in August and control system will be developed for integrated operation

Acknowledgements

- This work was supported by the DOE SunShot Program (SuNLaMP-0000000-1507)

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