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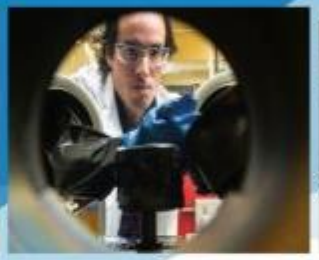

Particle-Based CSP System Development at NREL

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Concentrating Solar Power

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» Concentrating Solar Power » Research

- Materials Science
- Lab Characterization
- Field Characterization
- Engineering & Techno-Economic Analysis

Research

Research and development (R&D) capabilities in concentrating solar power (CSP) at the National Renewable Energy Laboratory (NREL) span the entire electricity system—from generation to transmission and distribution to the end user. NREL scientists and engineers pursue R&D and provide assistance in the following four areas.

Materials Science

Optical, thermal, and containment materials are critical to CSP systems, and their performance directly affects system-wide cost and efficiency. NREL

Lab Characterization

NREL scientists characterize the performance and durability of reflector and absorber materials, high-temperature heat-transfer and storage materials,

HTTP://WWW.NREL.GOV/CSP

Outline

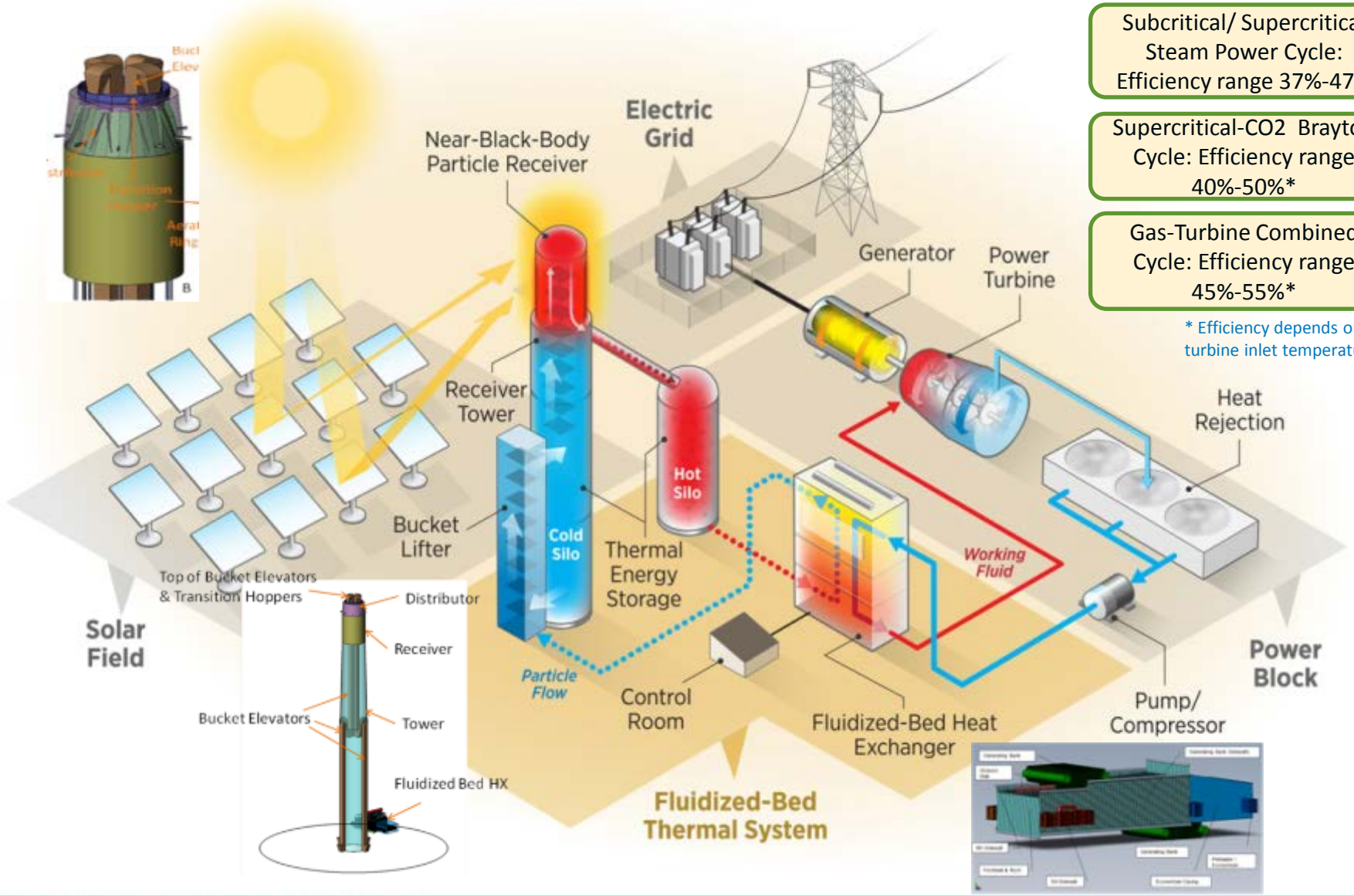
- Introduction
- Enclosed Particle Receiver Development
- Particle-Based Thermal Energy Storage
- Particle/Working Fluid (Steam and s-CO2) Heat Exchanger
- Particle Material Handling and Distribution

Particle-Based CSP System Projects at NREL

- Three DOE funded projects relevant to the particle-CSP development:
  - SunShot Project: Near-Blackbody Enclosed Particle Receiver integrated with fluidized-bed heat exchanger (2012-2015, NREL Prime, B&W and universities Subs, $3.8 million DOE funding +$0.9million cost share)
  - ELEMENTS Project: High-temperature thermochemical storage with redox-stable perovskites for concentrating solar power (2014-2016, CSM Prime, NREL, Abengoa Sub, $1 million DOE funding +$0.3 million cost share)
  - BRIDGE Project: Using Solid Particles as Heat Transfer Fluid for use in Concentrating Solar Power (CSP) Plants (2013-2015, CU Prime, NREL, ORNL Sub, $0.45 million DOE funding)
  - NREL AOP Project on Particle storage containment design (2012)
- Objectives:
  - Enable the high-temperature, low cost particle thermal system and drive high-efficiency power cycles.

Schematic of Particle-Based CSP System

NREL Vision and Major Development on a Particle-CSP Plant



Subcritical/ Supercritical Steam Power Cycle: Efficiency range 37%-47%

Supercritical-CO2 Brayton Cycle: Efficiency range 40%-50%*

Gas-Turbine Combined Cycle: Efficiency range 45%-55%*

* Efficiency depends on turbine inlet temperature.

Particle System Configuration Parameters

Receiver Parameters	Value	Comments
Receiver heat load	500 MW_{th}	The receiver has wide scalability,
Receiver thermal efficiency	> 90%	For 250-800°C particle temperature range.
Particle temperature rise @ 30°C/m	550°C	for 250°C cold-particle returning temp.
Hot particle exit temperature:	800°C	HTF Exit temperature
Support power cycles	> 650°C	Steam, Brayton (s-CO2 and air)
Power cycle rating	50-250MWe	TBD with plant economics and TES
Particle flow for 400MW_{th} receiver	610 kg/s	Based on *Cp*=1050 J/kg C
Solid particle size	100–300 µm	Median diameter <200 µm
Optical tower height	135 m	Receiver size Ø15 m X 20 m tall
Thermal energy storage	3–15 hrs	Depending on plant design

Particle-CSP System has good scalability with enclosed particle Receiver

- Wide receiver thermal capacity range
- Ability to drive different power cycles
- Economic TES for different capacities

Advancing CSP Technologies

- Potential improvement of performance
- Potential reduction of capital cost

System Variable	Molten Salt	SPR	SPR	SPR
Turbine Cycle	Sub-C Rankine	SC Rankine	Brayton (s-CO_2)	Brayton (Air)
Turbine Working Fluid	Steam	Steam	CO_2	Air and Steam
Receiver HTM	Nitrate Salt	Solid Particles	Solid Particles	Solid Particles
Receiver Exit Temp	566 °C	800 °C	800 °C	800 °C or higher
Heat Exchanger	Shell and Tube	Fluidized Bed	Fluidized Bed	Pressurized FBHX
HP Turbine Inlet	540 °C / 13 MPa	580 °C / 24.2 MPa	700°C / 25 MPa	Up to 1420 °C
Turbine Efficiency	42%	45%	51%	52%
Energy Storage (hr)	6-13	6-13	6-13	6-13

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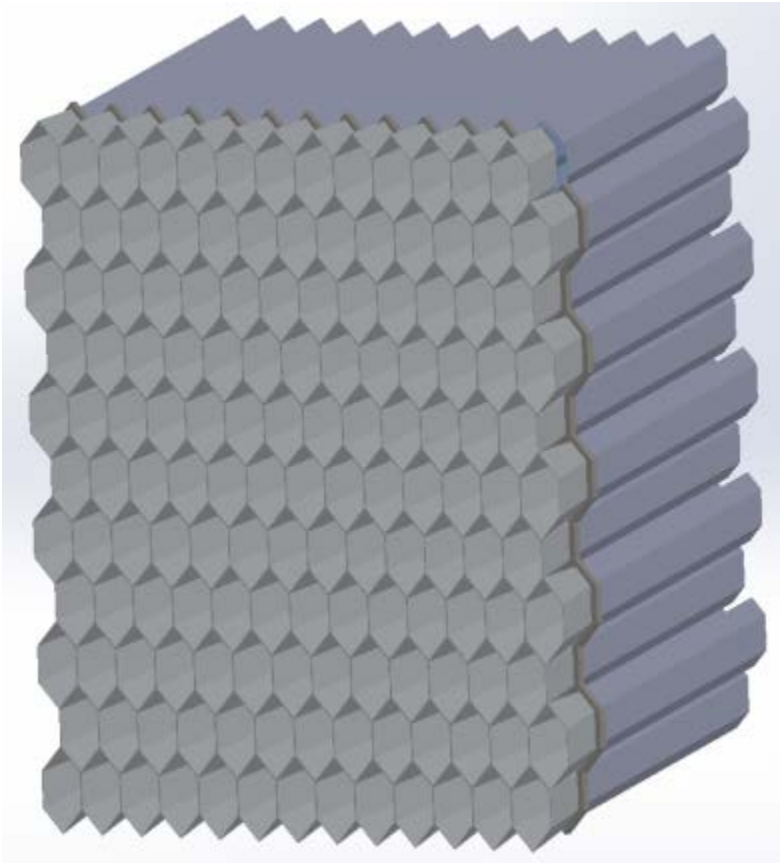
NREL Enclosed Particle Receiver —Tubular Absorber



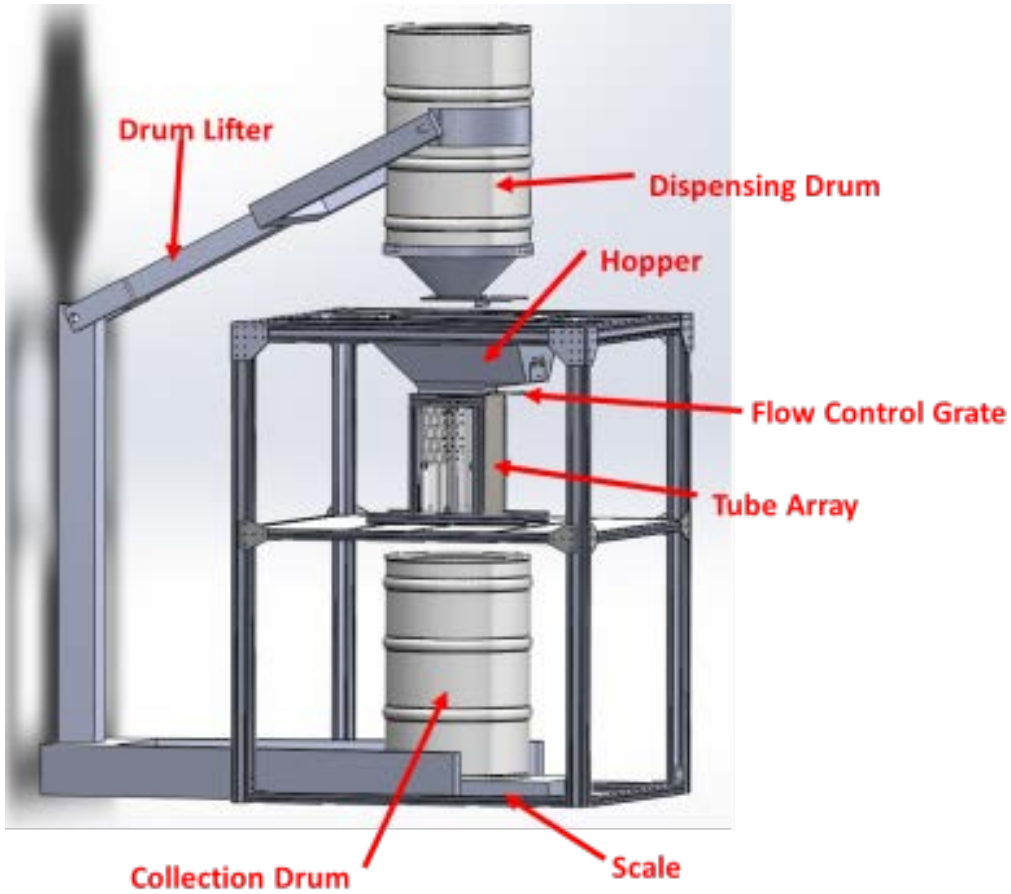
Design merits:

1. High thermal efficiency at high operating temperature.
2. Hexagonal tubes can be prefabricated and assembled.
3. High particle flow rate for scaling up to product receiver with surround solar field. No particle loss with the enclosed configuration.

Challenges:

1. Inner surface of the tube needs reflective coating for flux spreading.
2. Low temperature reflective flare limits the cycle options.

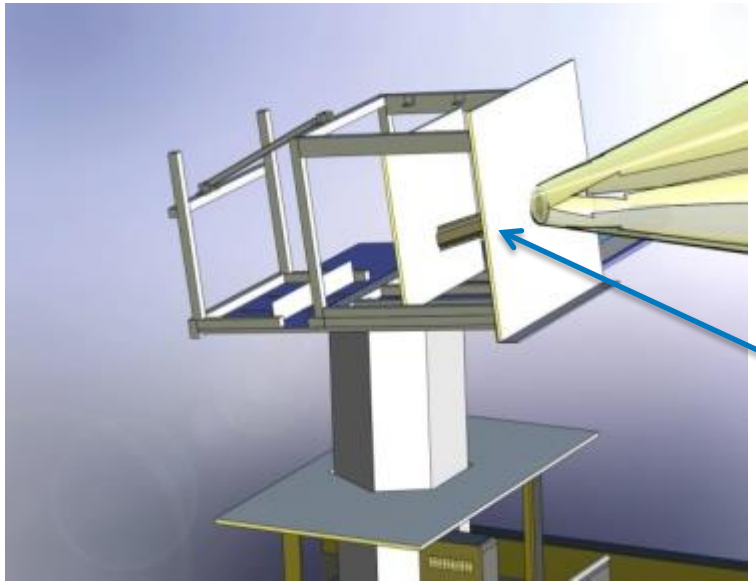
NREL Facilities Used in Support of Project

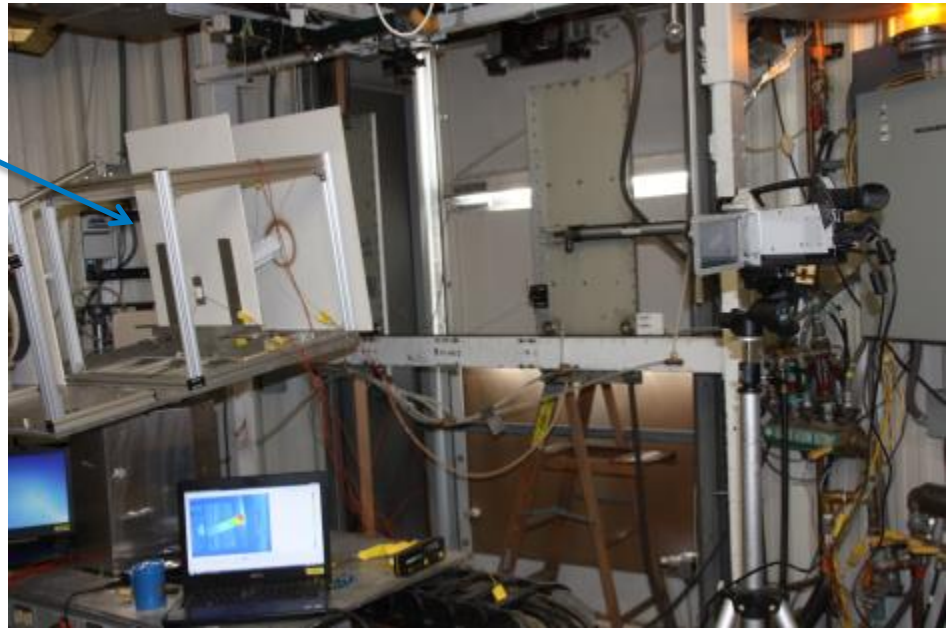


NREL Particle Flow/Heat Transfer Test Setup

Experimental Validation at NREL Solar Furnace

Absorber tube on-sun test at NREL solar furnace

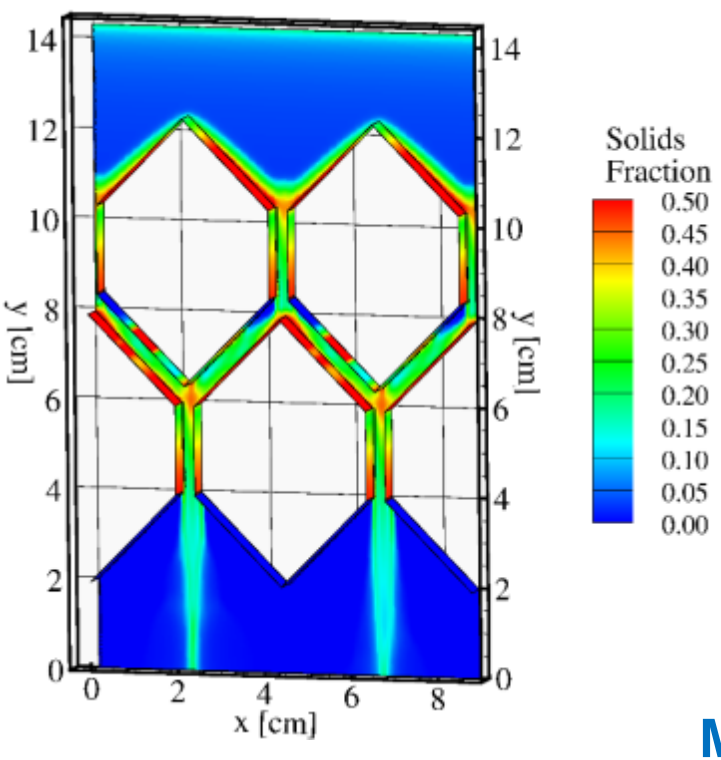


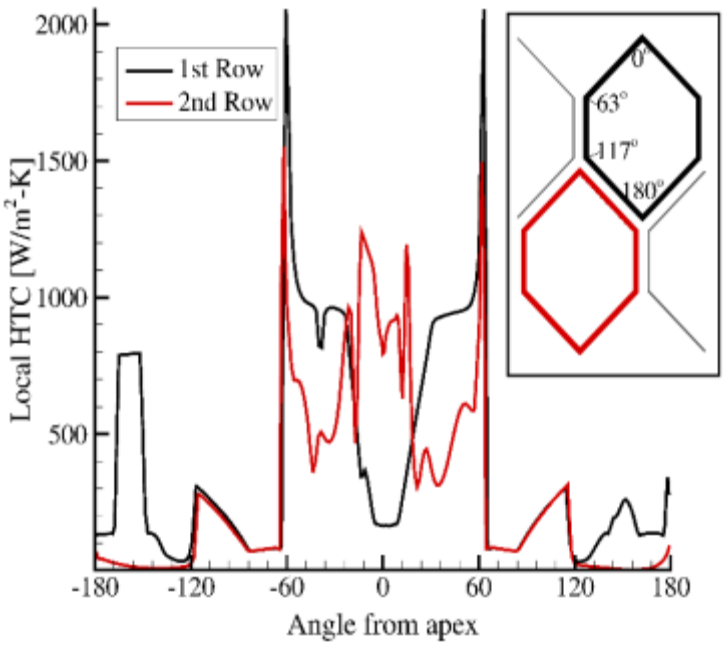


MFIX Simulations of Hexagonal Tube Array

Heat transfer in hexagonal array

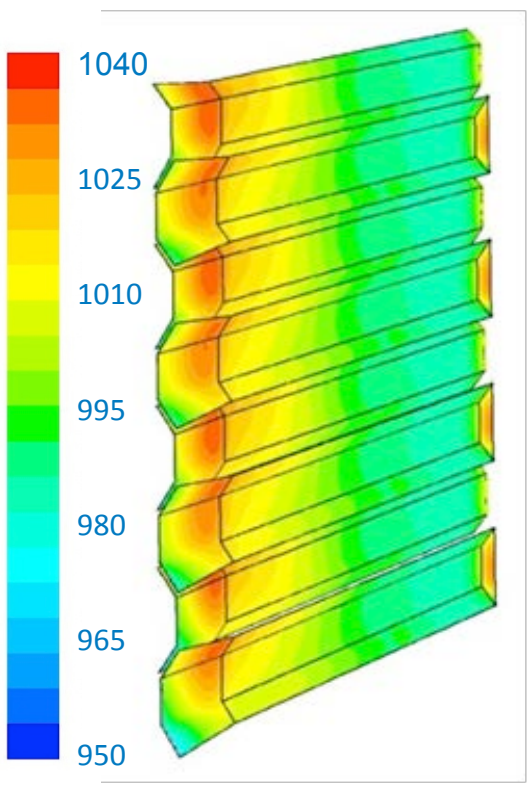
- Local heat transfer coefficient profile different for top and bottom rows
- Sharp steps in local heat transfer coefficient occur where particles attach/reattach
- Some heat transfer on bottom surface of hexagon (unsteady)

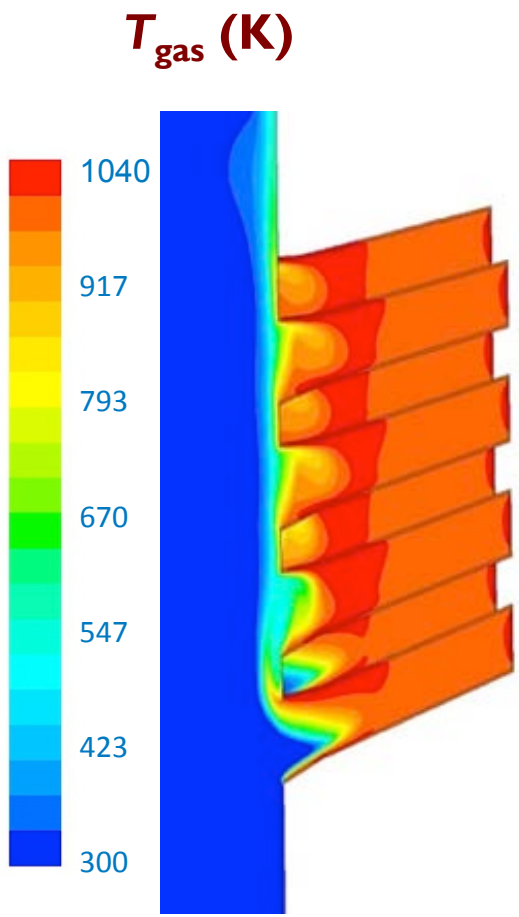




MFIX Simulation from BRIDGE Project

Detailed CFD Modeling of the Particle Receiver





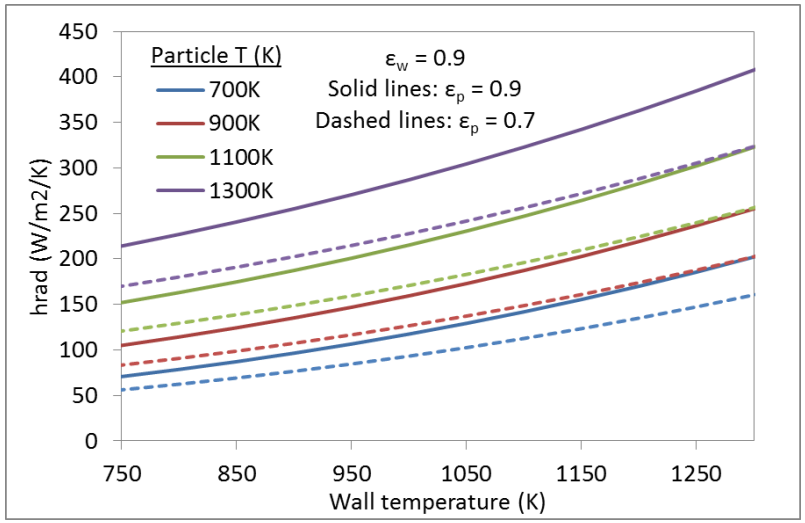
T_{part} = 973 K, $h_{T,conv}$=500 W/m^2·K,

Aperture flux = 500 kW/m^2

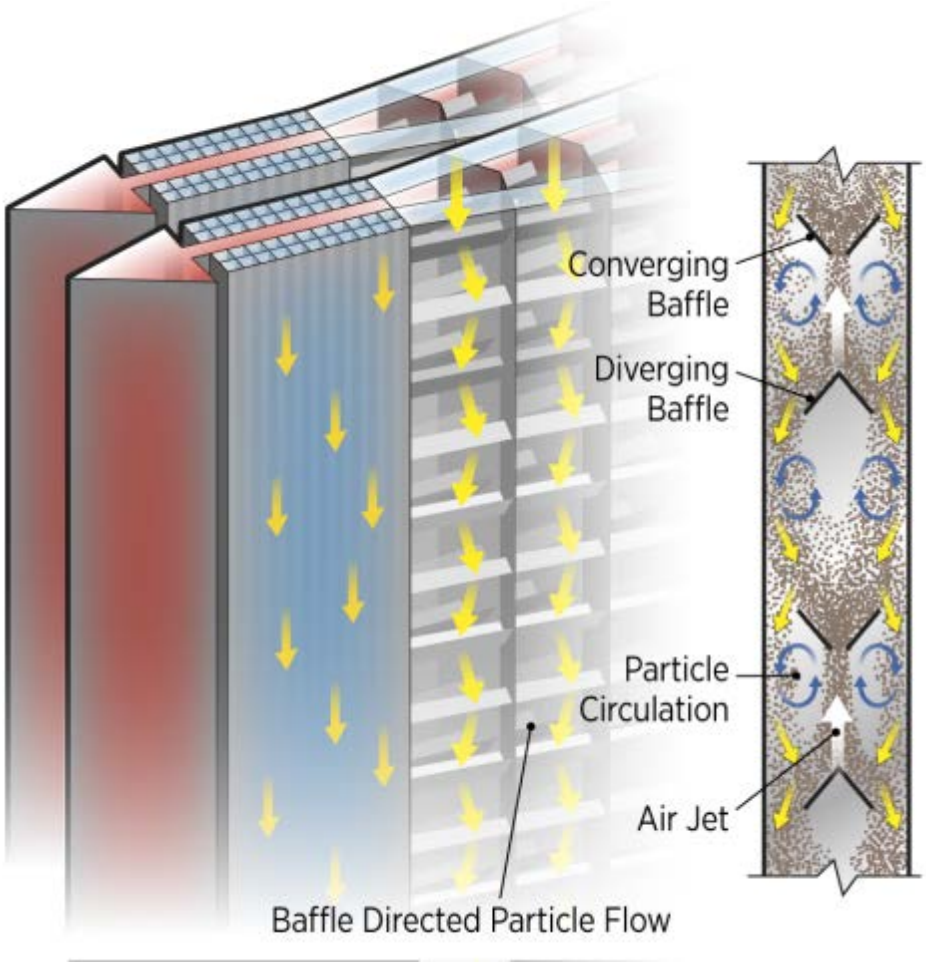
Assumptions:

- Constant T_{part}
- $h_{total} = h_{T,conv} + h_{rad}$
- $h_{T,conv}$ treated as parametric input
- h_{rad} calculated from local T_{wall}

Radiative heat transfer coefficient



Design 2: Planar-Cavity Receiver Design



NREL Patented Receiver Design

Design merits:

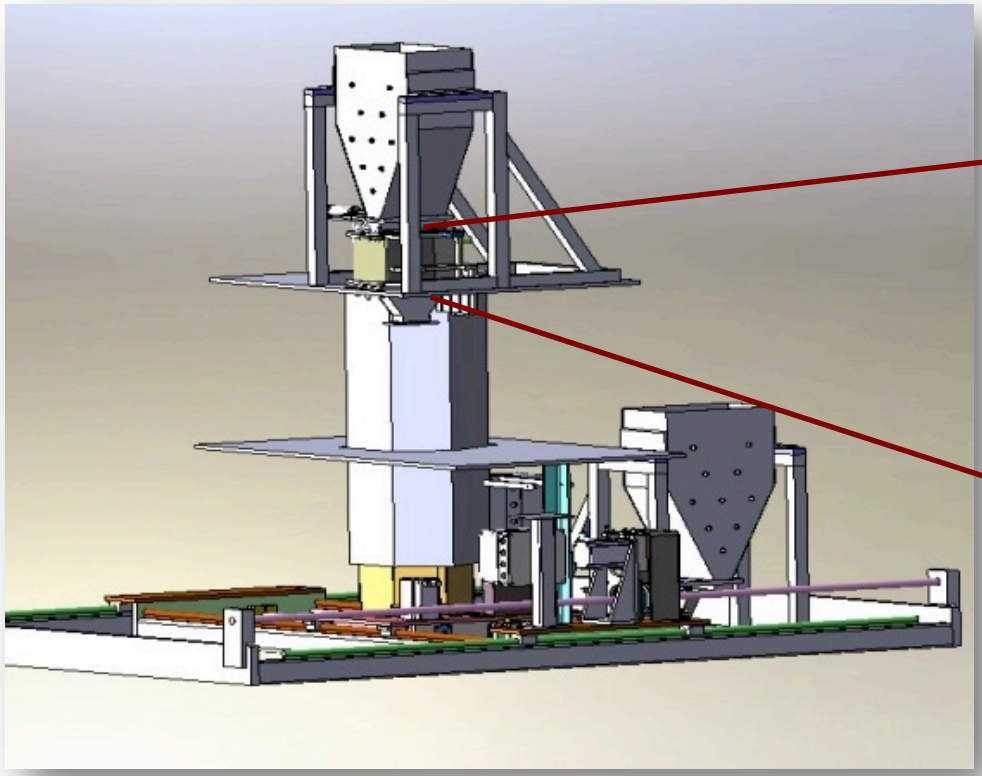
1. Avoid coatings.
2. High particle flow rate and no particle loss
3. High thermal efficiency.
4. Easy fabrication and scale-up with panel cavity formation.
5. Small-scale test was conducted at NREL solar furnace.

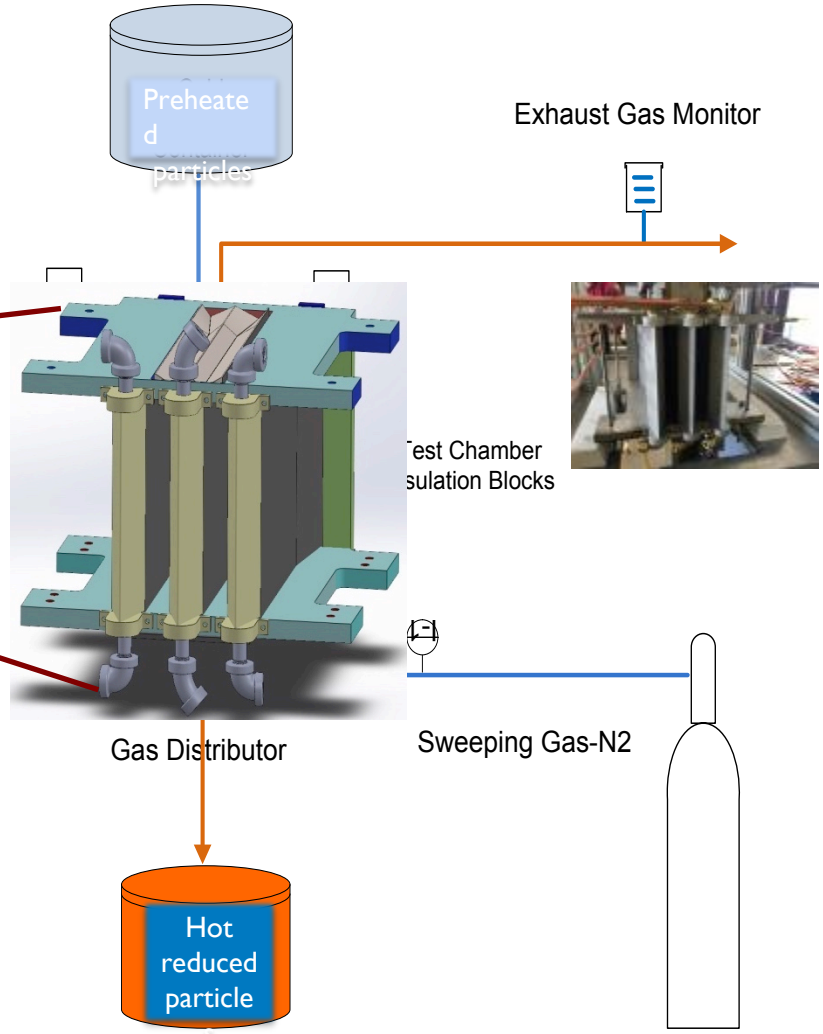
Challenges:

1. Implementation of heat pipes needs to be design and tested.
2. Particle flow and heat transfer need to be verified based on MFIX modeling results in DOE BRODGE project.

Assembling the Prototype Receiver at NREL Solar Furnace

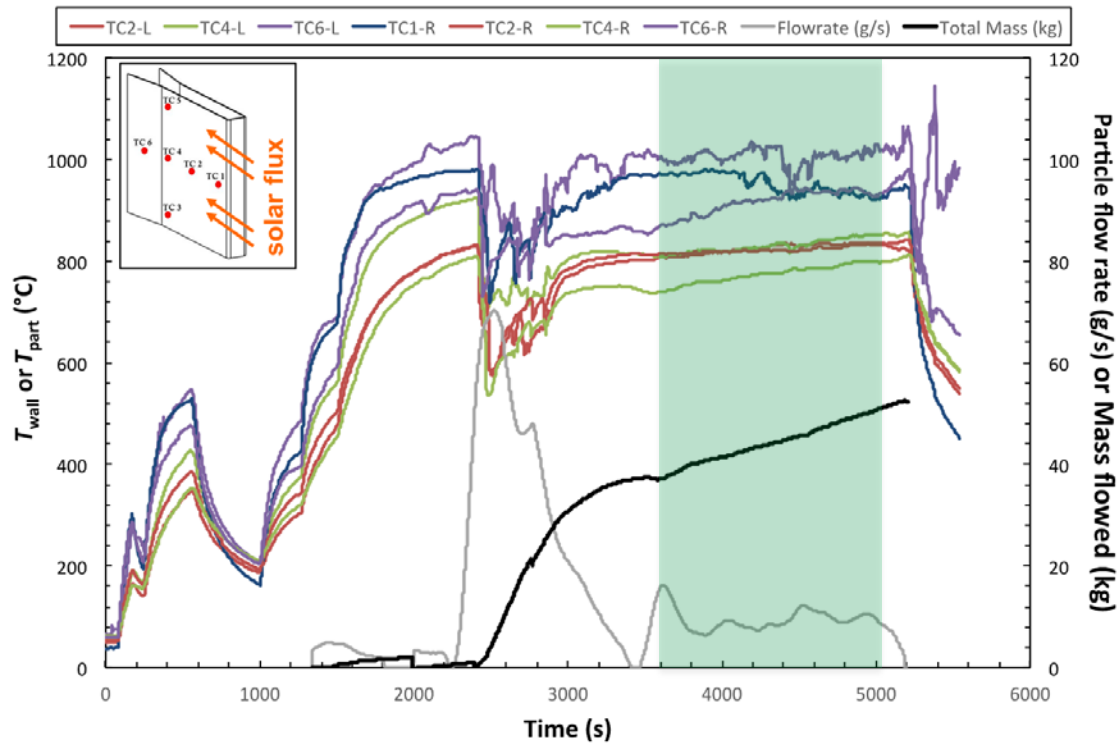
Assembly drawing of HFSF test facility without reoxidation reactor.





On-Sun Receiver Testing at NREL Solar Furnace

- Carbo Accucast ID50 particles
  - 200 μm < d_{part} < 300 μm
- For continuous tests, achieving particle fluidization with desired flowrates was very challenging.
- Particle flow rate regulated via two orifice plates.
  - Inlet: 0.058" wide slots
  - Outlet: 0.048" wide slots
- Particle to wall heat transfer is heavily dependent on flow characteristics.
  - 50° C particle ΔT observed through steady state region.



Transient evolution of receiver T_{wall} at locations shown in top-left inset. Particle flow is initiated after t = 2200 s and steady state conditions are achieved around t = 3500 s.

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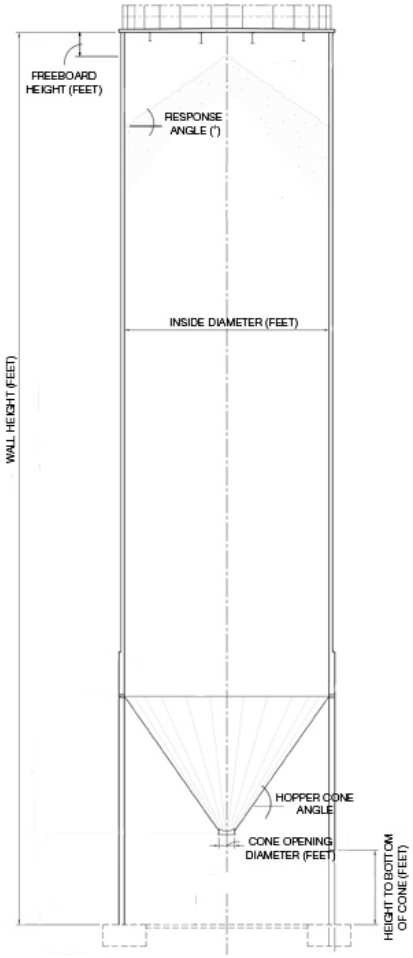
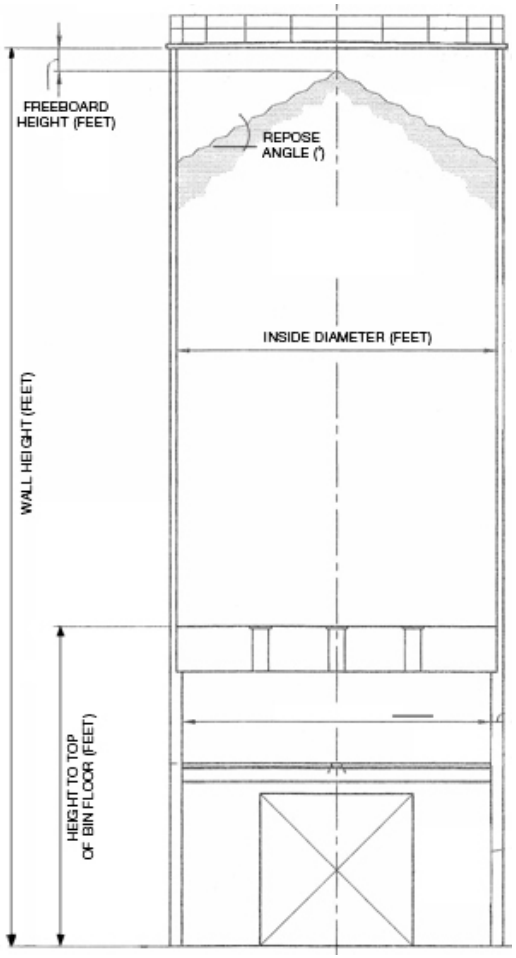
NREL Particle Storage Silo Design



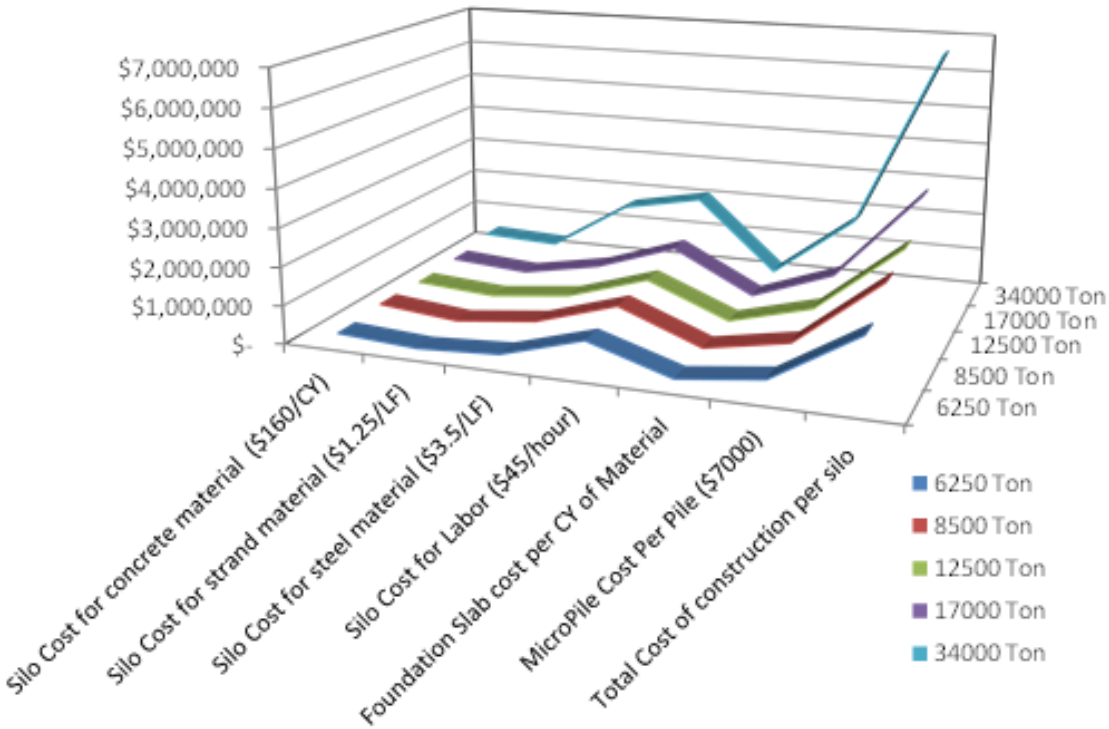
Cone bottom silo



Flat bottom silo

- Standard silo designs of Flat and Cone Shaped bottom.
- Consider to store particles at temperatures of 800-900° C
- Layers of insulation to maintain the silo surface at 200-300 ° C
- The silo will have a storage capacity of 17,000 tons of material at a cost ~3.5millioin, not including insulations.

Particle Storage Containment Cost



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2012 NREL AOP Work
Published in ASME PowerEnergy2017-3099

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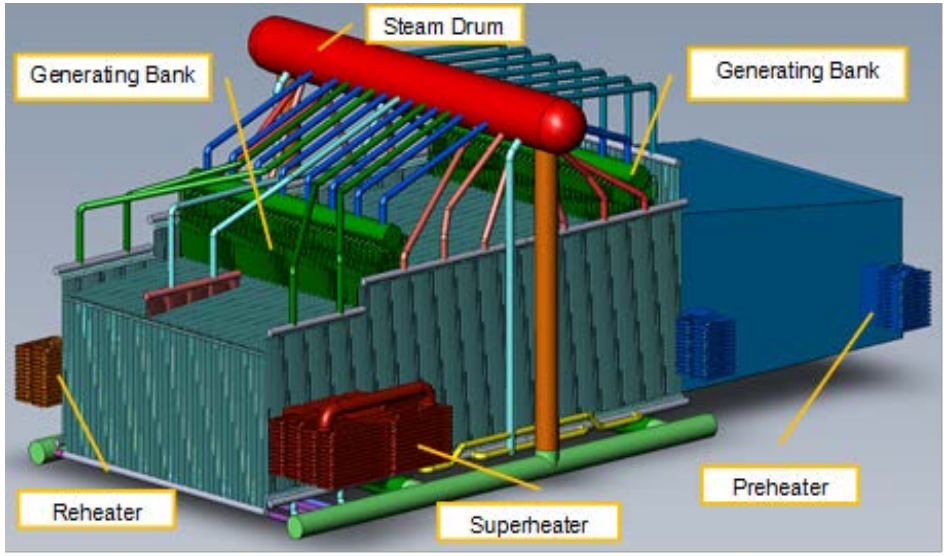
Fluidized Bed Heat Exchangers for Power Cycles

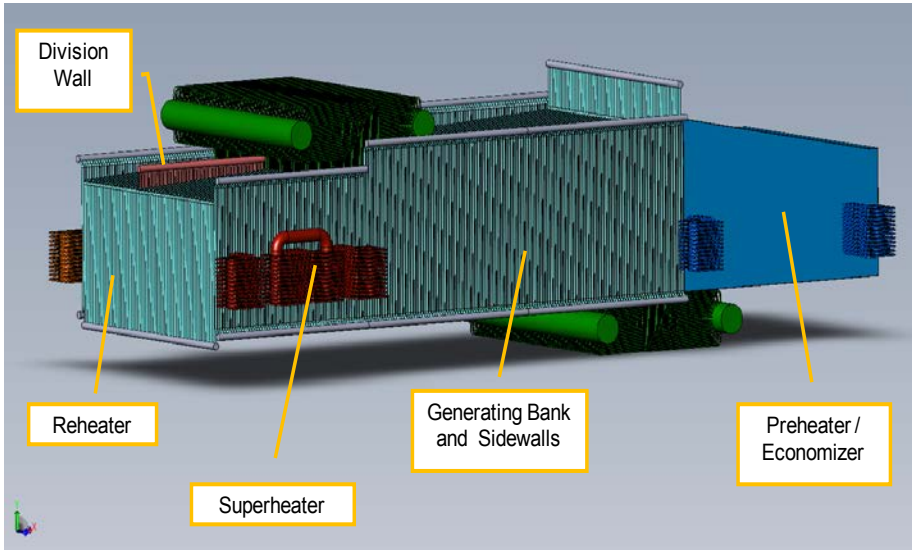
- Fluidized-Bed Heat Exchanger for S-CO_2 Power
  - More heat transfer area is needed for s-CO2 power system due to the small temperature difference from the power cycle.
- Pressurized Fluidized Bed Heat Exchanger
  - Air Brayton combined cycle
  - Direct air-particle contact
- Fluidized-Bed Heat Exchanger for Steam Power
  - Sub-Critical Steam FB-heat exchanger
  - Supercritical Steam FB-heat exchanger

Development with Babcock & Wilcox (B&W) Company through DOE SunShot Project (2013-2015).

Fluidized-Bed Heat Exchanger for Steam Power



Sub-Critical Steam FB-heat exchanger



Supercritical Steam FB-heat exchanger

B&W fluidized-bed boiler designs can be applied to conventional steam power generation, and then support the high-efficiency supercritical steam power system.

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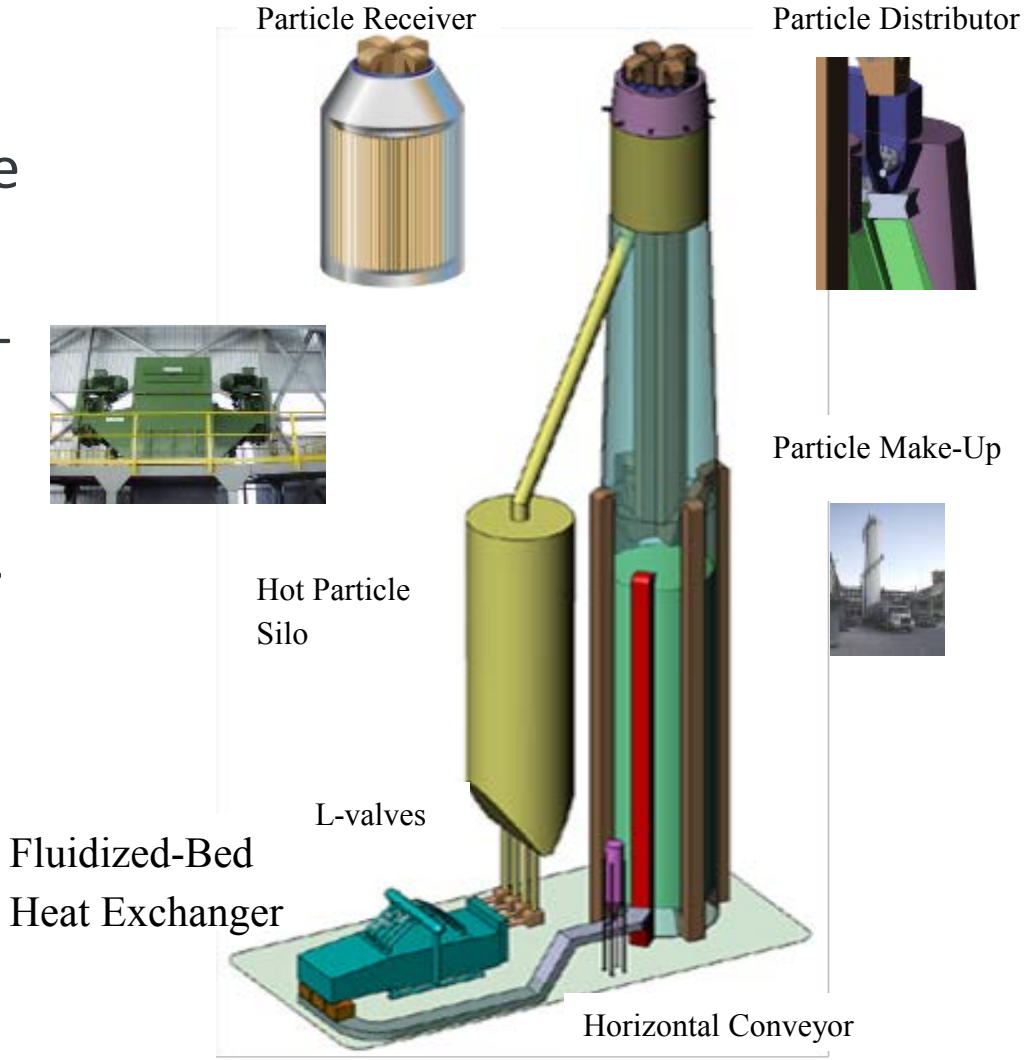
Integrated Particle Distribution System

- Comprised of commercially available equipment
- Totally enclosed (dust-tight) and insulated
- L-valves regulate hot particle circulation for load control
- Includes component redundancy



B&W particle-system design in DOE SunShot Project with NREL

Summary

- Particle-based CSP system can obtain efficiency gains coupled with capital cost reduction, and can substantially reduce the LCOE of CSP plants.
- Particle-based CSP system allows CSP plants to drive high-temperature advanced power cycles.
- Fluidized bed heat exchanger enables efficient heat transfer between particles and working fluids for Subcritical- and supercritical-steam cycles Supercritical-CO_2 cycles.
- Pressurized fluidized bed utilizing direct contact air heating can support air-Brayton combined cycle.

NREL Patents

- Relevant Patents
  - Ma Z, "*Methods and Systems for Concentrated Solar Power*", USPTO 9, 690 B2, Issued May 2016.
  - Ma Z, Turchi C, Martinek J, Wendelin T, Mehos M, Netter J, NREL ROI No. 14-72, "Receivers for Concentrating Solar Power Generation", USPTO Appl. 62/387,540, Filed December 24, 2016.

Questions?

Thank You!

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