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Design of Modular Test Facility for Particle/sCO_2 Heat Exchanger Evaluation

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Abstract. Heliogen has designed a 1.3 MW particle and supercritical carbon dioxide (sCO_2) test loop to retire technical and manufacturing risks. The data from this facility will be used to validate near commercial-scale particle heat exchanger modules. The heat exchanger is scaled to capture all features of the full-scale modules. Testing will be conducted with CARBOBEAD HSP 16/30, a larger particle size than other recent testing. The system was designed to ASME codes with the constraint that sCO_2 piping and other major components are stainless steels.

Keywords: Thermal Energy Storage (TES); Heat Transfer Fluid Air; Solid Storage System; Concentrated Solar Power; Third Generation Concentrated Solar Power

1. Introduction

Particle to fluid heat exchangers have been proposed to deliver the heat from particle based concentrated solar thermal collection systems to the turbines in the supercritical Carbon Dioxide (sCO_2) power cycle [1] Generally, these heat exchangers (often referred to as the primary heat exchanger or PHX) consist of diffusion bonded printed circuit heat exchanger (PCHE) plates with etched microchannels for sCO_2 flow. The plates are bonded with each other and to the headers to form the heat exchanger core. Between each set of parallel plates, there are gaps to allow for particle flow. The hot particles from the thermal energy storage (TES) system are transported to the top of the PHX where they are driven by gravity to a collection bin. As these particles flow through the PHX, their heat is transferred to sCO_2. At the PHX outlet, the sCO_2 exits at approximately 600 °C and 25 MPa. Particles enter the heat exchanger at 670 °C.

Due to the novelty of the application, extreme operating conditions and the use of relativity new manufacturing methods, there exists a risk of under-sizing, as well as mechanical failure of the PHX. Steep temperature gradients and thermal expansion of the heat exchanger plates contribute to large thermomechanical stresses in the heat exchanger. Furthermore, the performance of the heat exchanger is dictated by the thermal resistance of the particles. A review of the literature indicates that the thermal conductivity of moving particles may be lower than that of stationary particles[2]. This may result in degraded performance of the PHX compared to the predicted values.

Thus, it is critical to better understand the heat transfer phenomena in the particle/sCO_2 heat exchanger, characterize its thermal performance and to retire the thermomechanical risks described above. Heliogen has designed a 1.3 MW particle and sCO_2 loop to retire these risks (Figure 1). This test loop will be used to test a novel 1 MW PHX heat exchanger designed and manufactured in partnership with Vacuum Process Engineering (VPE), Solex Thermal Science, and Sandia National Lab (Figure 2). The data from this facility will be used to validate commercial particle heat exchanger module designs. The sCO_2 side of the loop will operate up to 28 MPa at 6 kg/sec. The particle side will use a compact air to particle heater. After the particles are heated to a simulated concentrated solar power (CSP) TES hot silo exit temperature they will flow through the primary test heat exchanger, a sCO_2 to particle cooler operating with 1 mm aluminosilicate ceramic particles in a continuous feed. Supporting standard hardware will also be tested at commercially relevant CSP conditions including sCO_2 dry cooler, sCO_2 wet cooler, sCO_2 valves, sCO_2 recuperator, sCO_2 pump, particle valves and particle bucket elevator. The facility equipment will be mounted on skids and a modular tower that can be erected at the initial test site in Southern California and moved to another site as required after test completion.

2. Test Loop Design

The test loop shown in Figure 1 and Figure 3 is designed for nominal state points shown in Table 1 and Maximum Allowable Working Pressure (MAWP) of 28 MPa. The ground-based air heater and sCO_2 loop allow for a high degree of flexibility in turndown of flow rates on the order of 10:1 for off design operation. In addition to off design steady operation, the test loop will help to better understand startup, transient and shutdown operations.

The particle side of the test loop will move a continuous loop of CARBOBEAD HSP 16/30 particles. These particles have a median diameter of 956 um[6], and are composed of material that has been previously investigated for use in CSP heat transfer and storage media [7]. The bucket elevator has a travel time of approximately 25 seconds. The bucket elevator feeds an inlet hopper to provide uniform particle mass flow at the inlet of the particle heater. The inlet hopper is sized to buffer increases and decreases in flow rate during the travel time of the elevator. Similarly, there are two hoppers located between the particle heater and the test unit, and at the outlet of the test unit. The flow rate through the test unit is controlled using a flow control valve located at outlet of the discharge hopper. From the inlet of the particle heater to the particle valve, the particles flow in a mass flow profile (uniform velocity profile). Chute angles were selected to be 35 degrees or larger from horizontal based on prior experience with Carbo particles and maximum allowable tower height.

The super critical carbon dioxide (sCO_2) piping was designed to ASME B31.1 Power Piping code. Maximum operating temperatures and pressures in the system were selected to allow selection of primarily 316/316L stainless steels. 347H stainless steel was required for the state point 4 and 8 locations due to elevated temperatures. Small diameter instrument ports as described in prior Sandia sCO_2 work [3,4] and shown in Figure 4 were used at all locations less than 538 °C (1000 °F). 1” instrument ports were selected elsewhere as fittings and pipe less than ½” size were not available that would meet the project schedule and code requirements at >538 °C (1000 °F). The sCO_2 recuperator has a bypass line which allows for efficient temperature trim control of the PHX inlet temperature, and also allows the fluid to stay in a supercritical state during filling and startup. The sCO_2 loop includes both wet and dry coolers to enable maximum heat rejection when needed while conserving water during turndown operation or during cool weather days when evaporative cooling may not be required.

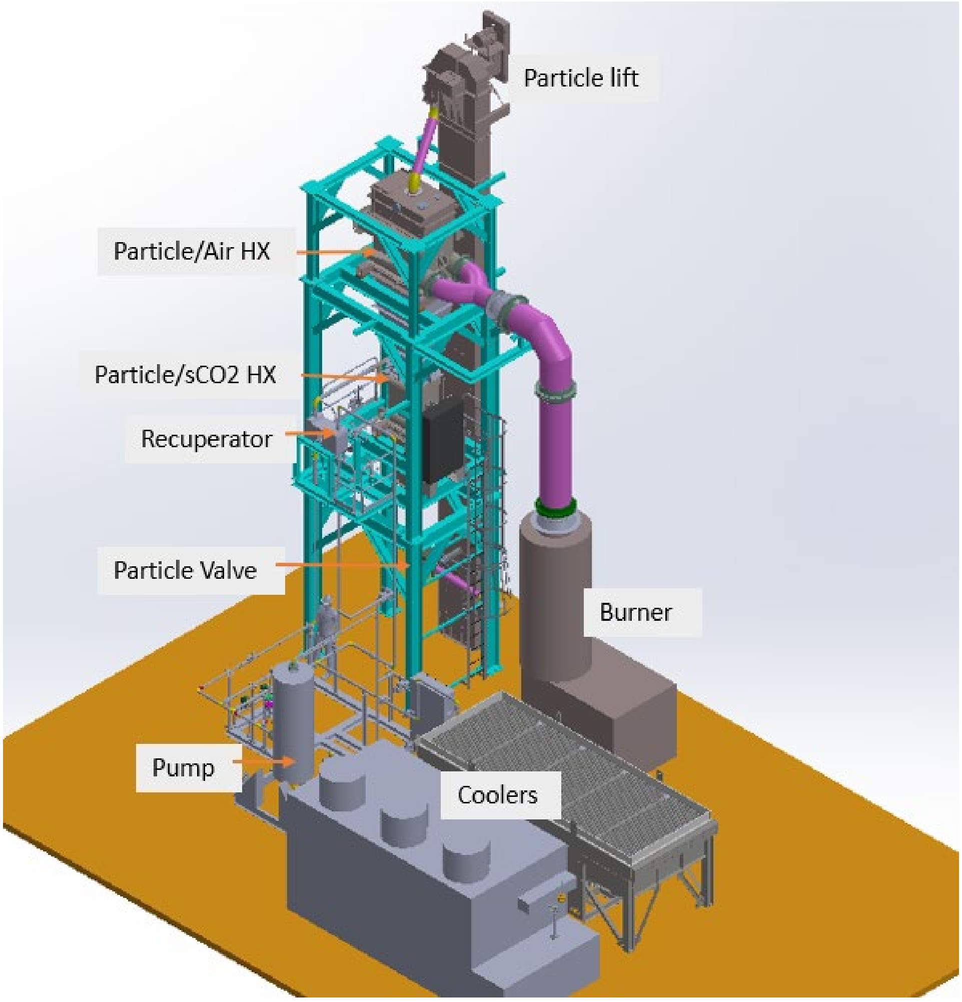

Figure 1. 1.3MW sCO_2 to Particle heat exchanger test loop layout.

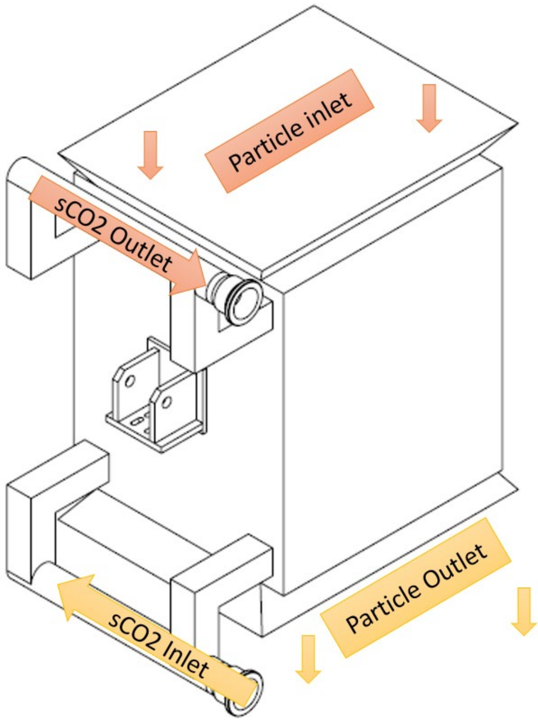

Figure 2. Defeatured model of the 1.3MW Particle heat exchanger manufactured by VPE.

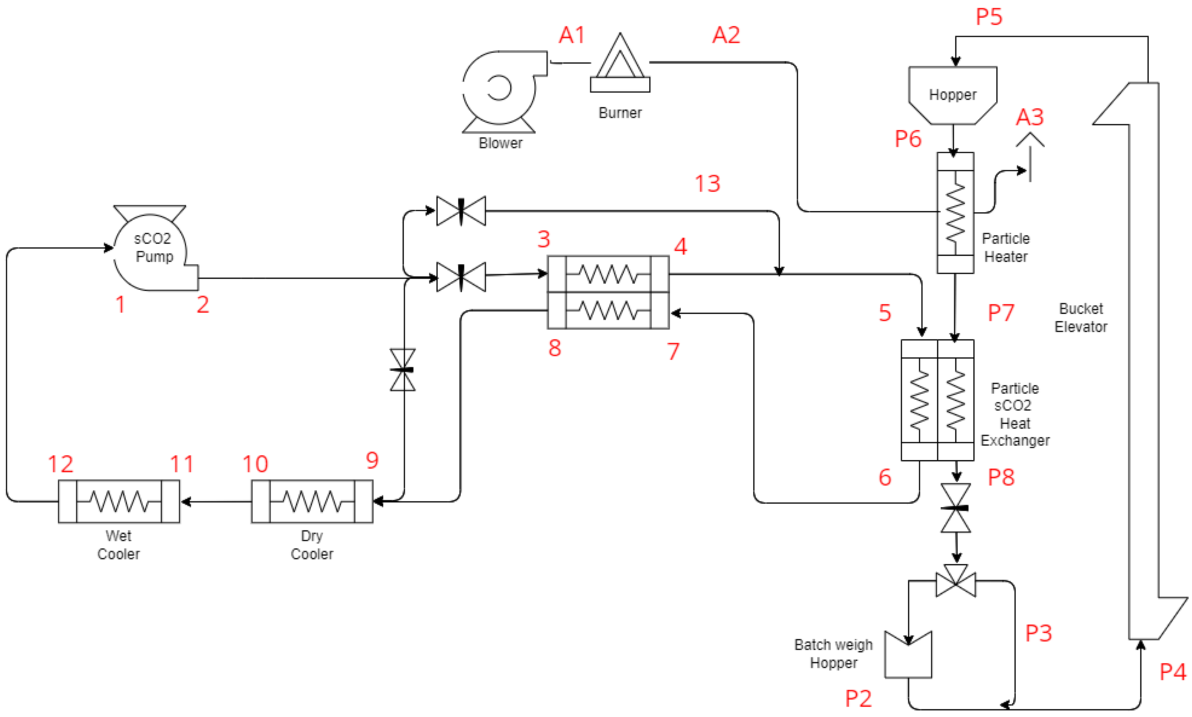

Figure 3. Heliogen 1.3MW sCO_2/Particle loop process flow diagram.

Table 1. Heliogen 1.3MW sCO_2/Particle loop nominal statepoints.

State Point	T C	P MPa	m_dot kg/s		State Point	T C	P MPa	m_dot kg/s
1	32	21.08	6.24		Air for particle heater			
2	32.8	22.47	6.24		A1	20	0.0175	4.52
3	32.8	22.37	5.175		A2	770	0.017	4.55
4	542.1	22.14	5.175		A3	510	0	4.55
5	436.8	22	6.24		Particle loop			
6	610	21.7	6.24		P2	470		5.79
7	610	21.51	6.24		P3	445		5.79
8	126.3	21.29	6.24		P4	445		5.79
9	126.3	21.22	6.24		P5	445		5.79
10	37.8	21.19	6.24		P6	670		5.79
11	37.8	21.16	6.24		P7	470		5.79
12	32	21.13	6.24		P8	470		5.79
13	32.8	22.42	1.065					

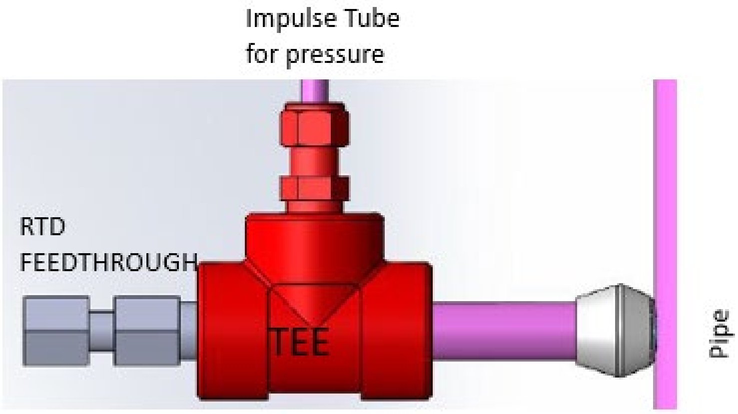

Figure 4. Instrument port used at locations <538 °C (1000 °F)

3. Test Objectives and Matrix

During the annual operation of a CSP plant, the heat output from the receiver varies drastically depending on the time of the day, weather conditions, reflective errors from heliostats, etc. These transient phenomena set the design requirements for the thermal energy storage system and coupled sCO_2 power block. The PHX of the sCO_2 power block may undergo temperature cycling from ambient to 600 °C. Thus, in addition to the high temperature creep damage, the PHX must also be designed to handle the fatigue damage that results from cyclic application of the thermomechanical stresses [5]. This is critical for meeting the life cycle requirements of the power plant.

The test article being investigated in this study is the first of its kind and the largest particle-sCO_2 heat exchanger built to date. The measured data from the testing will be compared to the results from our heat transfer models to validate these computational methods and give confidence to computational models of pilot plant equipment. Table 2 shows the test matrix planned for this effort. Initially, the testing will focus on steady state operation over the range of flow rates and temperatures expected during plant operation. Different turndown cases will be tested to better understand the particle momentum and heat transfer. Additionally, different moving packed bed thermal conductivity models will be tested against the data to determine the limits of their applicability.

Finally, PHX test data will also be collected as the heat exchanger undergoes transient events. These tests are meant to mimic the actual conditions that a CSP plant is expected to experience. The particle temperature ramp rate will be varied. When completely full, the PHX weighs more than 8 metric tons. Thus, it is expected to have a high thermal inertia which is why the particle ramp rates are relatively low, ranging from 5 °C/min to 20 °C/min.

3.1 Conclusion

Heliogen Holdings Inc. has designed and built a test facility for validating the performance of a novel 1.3 MW particle-to-sCO_2 heat exchanger. This PHX is a subscale replica of a commercial heat exchanger design for concentrated solar power plants. To the best of the authors' knowledge, this will be the largest PHX operated to date. The testing of this unit will serve as a proof of concept for future application of these heat exchangers in CSP plants and will provide valuable guidance for designing future heat exchangers. The facility is capable of heating the particles up to 670 °C and 6 kg/s. The sCO_2 loop was designed for 28 MPa and 610 °C.

Table 2. Test matrix for the sCO_2-particle heat exchanger.

Description	Objective	Target Particle Temperature [deg. C]	Duration [min.]	Particle Ramp Rate [deg. C/min]	Particle Mass Flux [%]	sCO_2 Mass Flux [%]
Steady-state power level #1	Performance validation	100	30	X	100%	100%
Steady-state power level #2	Performance validation	470	30	X	100%	100%
Steady-state power level #3	Performance validation	540	30	X	100%	100%
Steady-state power level #4	Performance validation	610	30	X	100%	100%
Steady-state power level #5	Performance validation	670	30	X	100%	100%
Repeat performance validation until satisfied						
Steady-state Particle turndown #1	Turndown characterization	670	30	X	80%	100%
Steady-state Particle turndown #2	Turndown characterization	670	30	X	60%	100%
Steady-state Particle turndown #3	Turndown characterization	670	30	X	40%	100%
Steady-state joint turndown #1	Turndown characterization	670	30	X	80%	80%
Steady-state joint turndown #2	Turndown characterization	670	30	X	60%	60%
Steady-state joint turndown #3	Turndown characterization	670	30	X	40%	40%
Steady-state joint turndown #4	Turndown characterization	670	30	X	20%	20%
Repeat turndown testing until satisfied (System starts at steady state)						
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 470	X	5	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 470	X	10	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 470	X	20	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	470 – 670	X	5	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	470 – 670	X	10	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	470 – 670	X	20	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 670	X	5	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 670	X	10	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	25 – 670	X	20	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	670 – 470	X	-5	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	670 – 470	X	-10	100%	100%
Particle Temp. Ramp Rate Testing	Thermo-mechanical screening / validation	670 – 25	X	-5	100%	100%

Data availability statement

No data has been generated yet from this work.

Author contributions

Shawn Maghzi (Conceptualization, Writing)

Tabeel Jacob (Writing, Investigation, Review)

Matthew Sandlin (Conceptualization, Supervision)

Matthew Carlson (Conceptualization, Supervision, Methodology)

Jack Hinze (Conceptualization, Review)

Competing interests

The authors declare no competing interests.

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