SAND2021-3291C

Particle-to-sCO_2 Heat Exchanger Experimental Test Station Design and Construction

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Abstract. Design and construction of a particle-to-sCO_2 heat exchanger test station is described in this paper. The purpose of~~to~~ this test station is to make steady-state measurements of thermal performance with sCO_2 as the working fluid.~~.~~ ~~Initially testing the prototype heat exchanger developed under the Gen3 particle pilot plant project and potentially other heat exchanger configurations.~~ While the test station was initially constructed to test a 20 kW heat exchanger ~~for use in~~developed under the Gen3 Particle~~-~~ pilot plant (G3P3) project, it also was designed to accommodate testing of other heat exchanger configurations. Improvements for this test station design is based on lessons learned from prior heat exchanger testing. Maximum pressure and temperature ratings are~~is~~ based on the desire to use ~~keep the construction materials of the test station~~ primarily stainless steel in the construction to reduce cost and lead time of~~n~~ components. Construction of the test station ~~in underway and~~was completed and commissioning and initial testing ~~is planned for the~~took place during the October to November 2020 timeframe.

INTRODUCTION

The performance and cost of particle-to-supercritical carbon dioxide (sCO_2) heat exchangers can have a significant impact on the economics of particle-based CSP plants [1]. Recent data collected from a prototype particle-to-sCO_2 heat exchanger at the National Solar Thermal Test Facility (NSTTF) of Sandia National Laboratories, has led to performance questions where experimentally measured values of overall heat transfer coefficient have deviated from design models [2, 3]. Therefore, there is a need for an integrated particle and sCO_2 flow loop with rigorous instrumentation for diagnostics to answer the underlying questions on particle heat exchanger performance and to test novel configurations that hold promise in low cost manufacturing or improved performance. This paper documents the design and construction of an experimental test station for evaluating prototype particle-to-sCO_2 heat exchangers up to 40 kW_{th}.

TEST STATION DESIGN SUMMARY

Design Layout

The system layout is illustrated below in Fig. 1, which shows the integrated geometric design. The particle flow loop is vertically integrated and relies on gravity driven flow to move particles through the heat exchanger. The connection to the heat exchanger interfaces can be easily disconnected in order to test various prototypes. An access platform is constructed around the heat exchanger for access to the electric heater and elevator outlet.

A process flow diagram of the particle-to-sCO_2 heat exchanger test station is displayed in Fig. 2. The heat exchanger test station is comprised of integrated particle and sCO_2 flow loops to allow for continuous testing of heat exchanger performance at steady-state conditions. Many tests that have been documented in the literature have used

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batch mode testing and electrically heated walls to measure particle heat transfer coefficients [4]. Currently, there is very little data available for steady-state performance with a sCO_2 working fluid.

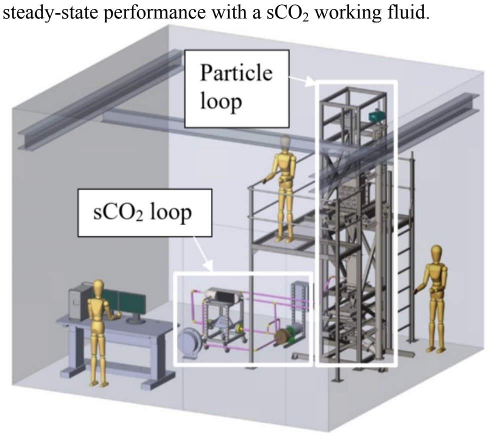

FIGURE 1. Drawing of heat exchanger test stand design layout, showing the sCO_2 and particle loops.

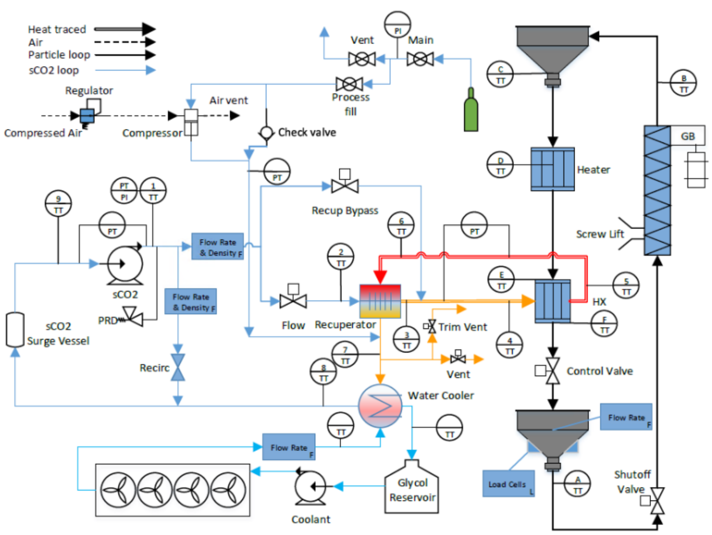

FIGURE 2. Process flow diagram indicating the layout of the integrated particle and sCO_2 flow loops

Design Specifications

The particle loop is electrically heated to provide accurate control over particle inlet temperature and is designed to provide inlet temperatures up to 600 °C, at flow rates of 0.2 kg/s. Recirculation of the particle flow is accomplished using a screw auger that was constructed from common stainless steel ~~grades~~ pipe sections and is capable of 0.4 kg/s particle flow and rated for 550 °C operating temperature. Instrumentation on the particle side employs a weigh hopper for measuring particle flow rate, thermocouples for making accurate boundary temperature measurements, and electric heater power monitoring for quantifying the thermal duty. Additional instrumentation was~~is planned to be~~ included in the particle heat exchanger to measure temperature profiles of the metallic components for robust model validation data.

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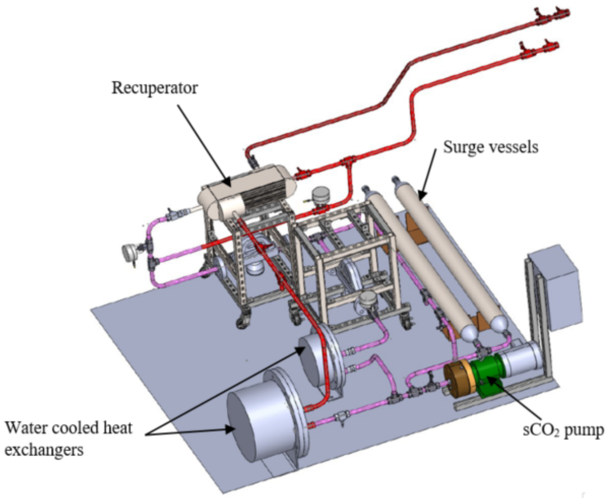


FIGURE 3. sCO_2 flow loop detailed design drawings with main equipment – particle-to-sCO_2 heat exchanger not shown here

The sCO_2 flow loop, as show in Fig. 3, is an isobaric system that includes a high-pressure dense phase pump, Coriolis flow meter, recuperator, and water-cooled heat exchanger. Actuation of throttle and bypass valves allows for complete control of flow rate and inlet temperature for the particle heat exchanger. The operating pressure and temperature of the system is 17 MPa and 535 °C, respectively. These operating conditions are currently below the targets for Gen3 sCO_2 power cycles (25 MPa, 700 °C), but it was desired to keep the construction materials of the test station primarily stainless steel to reduce cost and lead time on components. Future modifications are being considered to bring the operating temperature and pressure up to Gen3 targets. The maximum allowable working pressure (MAWP) for the system described in this paper is 20 MPa.

The design specifications for the first heat exchanger~~,~~ that is planned to be tested in this heat exchanger test stand~~,~~ is summarized in Table 1. Although this heat exchanger is rated for 20 kW_{th}, the test station is designed for particle-to-sCO_2 heat exchangers with a thermal duty up to 40 kW_{th}. The ~~design~~ system layout ~~is~~ can also accommodate~~ing~~ different design configurations of ~~the heat exchanger~~a particle flow layout. Experimental heat exchangers can be switched out and operated under various conditions to test the thermal performance of various design changes.

TABLE 1. Design specifications of 20 kW_{th} heat exchanger

Design metric	Parameter value	Units
Thermal Duty	20	kW_{th}
Design Temperature	550	°C
Design Pressure (MAWP)	20.0	MPa
Operating Pressure	17.0	MPa
Particle Inlet Temperature	500	°C
Particle Outlet Temperature	340	°C
Particle Mass Flow Rate	0.112	kg/s
sCO_2 Inlet Temperature	290	°C
sCO_2 Outlet Temperature	450	°C

sCO_2 Mass Flow Rate	0.103	kg/s
sCO_2 Pressure Drop	<40	kPa

The G3P3 heat exchanger geometry is used as the basis for the parallel plate design. The important design features to capture include close plate spacing (~3 mm), integral sCO_2 ports, single particle inlet and outlet, and hopper flanges brazed to the heat exchanger case. The baseline heat exchanger design is shown in Fig. 4. Many of the same design features present in the G3P3 heat exchanger are implemented here, except it is possible to feed the reduced heat exchanger size using a single inlet and outlet port on the sCO_2 side. The overall height of the heat exchanger including inlet and outlet hoppers as well as flow control is kept below one meter so that the unit can fit within the particle flow loop available height.

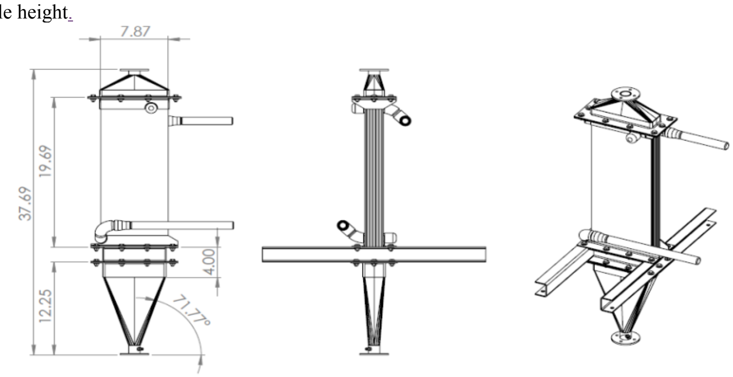
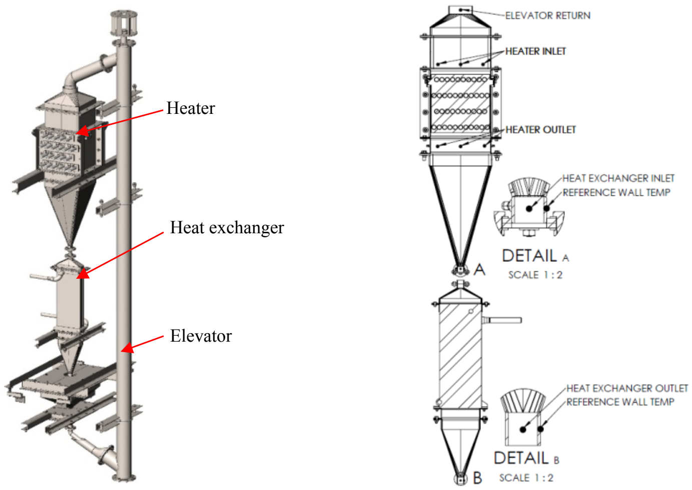


FIGURE 4. Drawing of the 20-kW parallel plate subscale prototype with design features that are relevant to the baseline G3P3 geometry (dimensions in inches).

Instrumentation and Controls

Particle Loop



(a) (b)

FIGURE 5. a) Particle flow loop main components, b) temperature instrumentation design layout

Main components for the particle flow loop are~~is~~ shown in Fig. 5 a), and the temperature instrumentation layout for the particle loop is described in Fig. 5 b). A set of temperature measurements upstream and downstream of the electrical heater provide a range of temperatures to obtain a representative average bulk temperature of the particles before and after the heater. The bulk particles entering the heat exchanger are funneled down to a small diameter tube to ensure thorough mixing of the particle regions at different temperatures, with a similar configuration at the outlet of the heat exchanger. This stems from lessons learned during previous temperature measurements in the experimental testing in other facilities.

Particle flow control through the heat exchanger is controlled with a slide gate below the heat exchanger that has proportional control. Mass flow measurements are done in a batch mode fashion with a small, inline hopper that is on load cells. Operation of the screw lift is continuous, running at a constant speed.

sCO_2 Loop

Instrumentation on the sCO_2 loop mainly comprise of temperature and pressure measurements. Temperature readings at the inlet and outlet of all main components are used for defining the operational states under different operational conditions. For an overall energy balance to be calculated, accurate and representative temperature and mass flow measurements are required. Coriolis flow meters provide the mass flow together with the density of the sCO_2 in the system, where the mass flow is an integral measurement in the energy calculation and the density is critical for safe pump operation. Pressure transmitters with the relevant sensitivities are used to measure the differential pressure across and heat exchanger and for measuring the static pressure in the system.

Temperature control within the various components in the sCO_2 loop can be achieved by manipulating two main factors, such as heat addition and flow configuration. Firstly, the particle-to-sCO_2 heat exchanger serves as the source of heat addition to the sCO_2 loop. The heat absorbed by the sCO_2 is then transported in the flow loop to the main water cooled heat exchanger to effectively dump the heat from the system again. The rate at which energy is moved from the particle-to-sCO_2 heat exchanger and the chosen operational temperature of the heat exchanger can be controlled by the amount of flow that is recuperated. More recuperation simply means that more heat stays in the particle-to-

sCO_2 heat exchanger sub loop, and that the overall operating temperature of the heat exchanger settles at a higher level.

The sCO_2 loop is equipped with a pump recirculation- and recuperator bypass-line. A combination of the valve settings enable the operator to accurately control the mass flow through the heat exchanger, while maintaining the desired level of recuperation to reach the optimal~~wanted~~ operating conditions. External heaters installed on the lines between the particle-to-sCO_2 heat exchanger and the recuperator ~~will~~ assist with the trim heating in case of tight temperature control and to mitigate some thermal losses from the tubing.

PRESSURIZED AND PARTICLE FLOW SYSTEMS – LESSONS LEARNED

Lessons learned from previous particle-to-sCO_2 heat exchanger operation contributed greatly to the design of this heat exchanger test station. Layout of instrumentation, flow control hardware and flow measurement methods are taken into consideration here. Temperature dependence of particle mass flow through the slide gate is a known phenomenon and will be accounted for by calibrating the slide gate at the operational temperature. For obtaining a representative and uniform particle temperature leaving the electrical heaters, flow is channeled into a small cross sectional area to equilibrate in temperature over a short diffusion length, even if uneven temperature distribution does exist. For future improvements, an in-line particle mass flow measurement device is recommended that is capable of measuring mass flow continuously.

On the sCO_2 loop, the two main improvements/changes are the implementation of higher resolution flow control valves and provision for additional cooling of the inlet flow to the pump during peak summer months. Due to the nature of a supercritical fluid, the sensitive coupling between heat addition and pressure calls for a very fine control over temperature gradients and heat addition to the different regions in the loop. To maintain the minimum operational density, the cold side of the loop needs to be cooled down to slightly below ambient temperatures, therefore a chiller combined with a water cooled heat exchanger on the pump recirculation loop will provide sufficient cooling.

CONSTRUCTION ~~PROGRESS~~

~~Construction~~ progress of the sCO_2 loop and the particle flow loop during construction ~~are currently underway and~~ depicted in ~~some~~ descriptive photos can be seen in the Fig. 6. An in-house developed and constructed screw type elevator was built and tested at the NSTTF. The final p~~P~~lumbing for the sCO_2 loop connection to the heat exchanger was installed with the ~~is near complete and the final lines will be installed with the~~ particle-to-sCO_2 heat exchanger in place.

(a) (b) (c)

FIGURE 6. Photos illustrating the construction progress of the heat exchanger test station. a) Particle flow loop support structure, b) sCO_2 loop installed, c) Screw lift internal details

A list of the major components, construction materials and the rating of the equipment and materials used to construct this heat exchanger test station is summarized in Table 2 below. The general operating pressure and temperature of the sCO_2 side of the system is 17 MPa and a range of temperatures from ambient to a maximum of <400 °C.

TABLE 2. List of major components and construction materials

Component	Material	Rating (operating exposure)
sCO_2 pump	Stainless steel	345 bar at 343 °C (ambient temperature)
sCO_2 Recuperator	Stainless steel	20 MPa at 550 °C (500 °C)
sCO_2 water heat exchanger	Stainless steel	20 MPa at 135 °C (±100 °C)
sCO_2 plumbing and fittings	Stainless steel	22 MPa at 537 °C (<500 °C)
sCO_2 filling compressor	Multiple	27 MPa at ambient temperature (ambient temperature)
Particle-sCO_2 heat exchanger	Stainless steel	20 MPa at 550 °C (500 °C)
Particle heater	Stainless steel	600 °C (535 °C)
Particle elevator	Stainless steel	550 °C (<400 °C)

CONCLUSION

The design of a particle-to-sCO_2 heat exchanger test station was presented for making steady-state measurements of thermal performance with sCO_2 as the working fluid. Construction of the experimental test station was completed ~~is currently underway~~ and testing for a prototype heat exchanger developed under the Gen3 particle pilot plant project ~~is planned for~~took place during November 2020 to March 2021.

ACKNOWLEDGEMENTS

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