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Integration of Supercritical Carbon Dioxide Cooling Loop for G3P3 Primary Heat Exchanger

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Abstract. The progress of development and construction of the Generation 3 Particle Pilot Plant (G3P3) supercritical carbon dioxide (sCO_2) cooling loop is presented. An introduction to the goals and overall rationale is described. Major components and instrumentation and piping systems are described. The layout of the sCO_2 cooling loop within the G3P3 tower is shown.

Keywords: Concentrating Solar Power, CSP, Supercritical Carbon Dioxide, G3P3, Power Cycles, sCO_2

Introduction

The Generation 3 Particle Pilot Plant (G3P3) being built at Sandia National Laboratories' National Solar Thermal Test Facility (NSTTF) will demonstrate the particle-to-supercritical carbon dioxide (sCO_2) technology at a 1 MW_{th} scale [1, 2]. An important aspect of G3P3 is the demonstration of a 1 MWth particle-to-sCO_2 primary heat exchanger (PHX) to evaluate the heat transfer between the heat transfer fluid (HTF) and the working fluid in a sCO_2 power cycle above 700°C. Although G3P3 does not contain a turbomachinery system for electricity production, the potential to reach the required temperatures for a high efficiency sCO_2 power cycle will be demonstrated.

G3P3 Supercritical Carbon Dioxide Cooling Loop

Description

Supercritical carbon dioxide (sCO_2) power cycles have been studied for several decades and have been found to be feasible for different applications including nuclear, fossil-fuel, concentrating solar, and waste heat recovery plants [3-5]. For CSP applications, the recompression Brayton cycle has been the baseline [6, 7] due to the potential thermodynamic efficiencies above 50% needed to make the cycle cost competitive when integrated with CSP plants.

As described previously, the G3P3 sCO_2 system does not contain a turbomachinery system that can produce electricity. Rather, the sCO_2 loop will serve as a cooling loop to demonstrate the system capability to remove heat from the particles in the PHX and the capability to generate sCO_2 above 700°C, simulating turbine inlet temperature (TIT) capable of reaching cycle efficiency targets. No measurements to verify the electrical efficiency of the G3P3 power cycle will be performed.

Figure 1 shows the flow diagram of the current sCO_2 cooling loop design with the thermodynamic states shown and defined in Table 1. The working fluid will be circulated by a

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water pump (modified for operation with high density sCO_2). This system will be capable of being retrofitted into a full recompression Brayton cycle. A previous publication shows more information about design details and rationale [8].

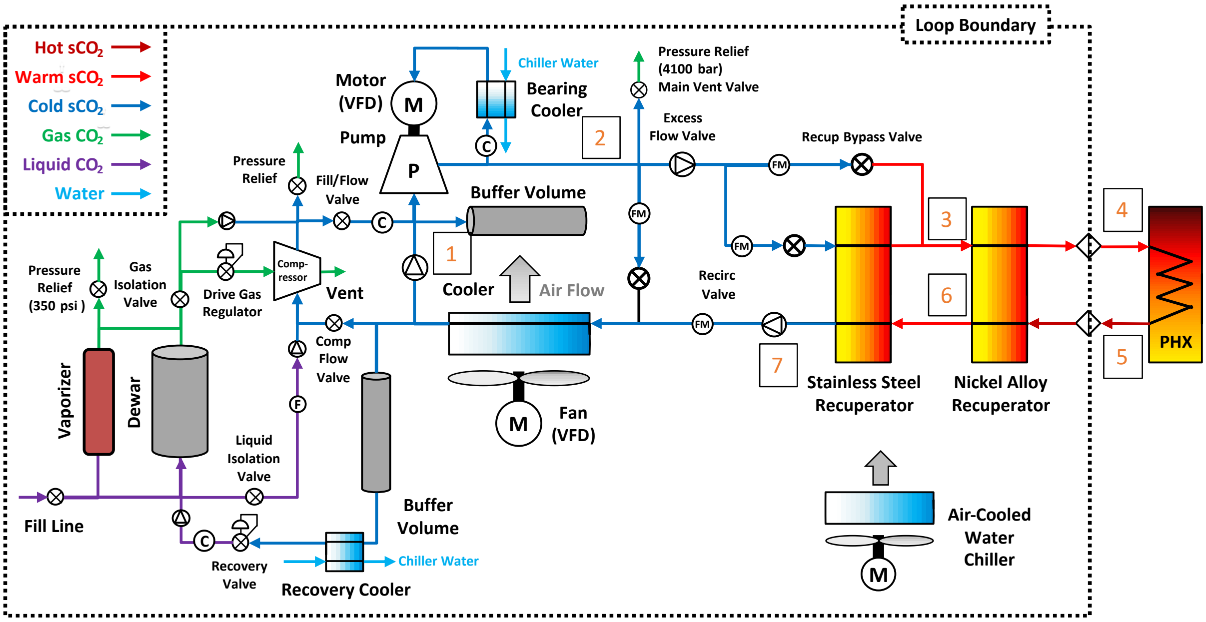

Figure 1. G3P3 Supercritical carbon dioxide cooling loop flow diagram

Table 1. G3P3 Supercritical carbon dioxide cooling loop thermodynamic states

State ID	State Description	Temperature	Pressure	Density	Specific Enthalpy	Specific Entropy	Dynamic Viscosity
		[K]	*[Pa]*	*[kg/m³]*	*[J/kg]*	*[J/kg-K]*	*[kg/m-s]*
1	*Pump Inlet*	328.9	2.43E+07	800	-200,003	-1463	7.144E-05
2	*Pump Outlet*	330.7	2.59E+07	806.6	-198,013	-1463	7.261E-05
3	*High Temperature Recuperator Inlet*	696.5	2.56E+07	190.4	366,224	-260.1	3.494E-05
4	*PHX Inlet*	838.2	2.54E+07	152.9	543,624	-26.36	3.863E-05
5	*PHX Outlet*	988.2	2.50E+07	126.6	733,954	185.5	4.258E-05
6	*High Temperature Recuperator Outlet*	848.2	2.48E+07	147.4	556,555	-6.082	3.881E-05
7	*Low Temperature Recuperator Outlet*	419.7	2.45E+07	415.5	-7,682	-945.4	3.473E-05

Requirements

High-level requirements for the sCO_2 cooling loop were defined as part of the Department of Energy's Solar Energy Technologies Office (SETO) Generation 3 program and are shown in Table 2. Derived requirements for this system were negotiated with the G3P3 team to ensure that the operation of the integrated system supports the overall objectives of the project. These requirements are mainly addressed by the major components:

- Circulation Pump
- Air-to-sCO_2 Dry Cooler
- Recuperation System

These components are described in subsequent sections.

Table 2. Generation 3 sCO_2 loop requirements

Requirement	**Value**
Operating Fluid	Carbon dioxide
PHX outlet pressure	≥250 bar
PHX outlet temperature	≥715°C
Thermal duty	≥1 MW_{th}
Operational time	≥16 hours/day
Mass flow rate (Derived)	≥5.3 kg/s

Components

Circulation Pump

A seal-less canned-motor centrifugal pump (Chempump Model NCRV-3X2-N7-41S by Teikoku USA) is the circulator for the sCO_2 in the cooling loop (Figure 2). Sandia has ample experience constructing and operating sCO_2 and particle systems for CSP applications, most recently under the SuNLaMP program [9]. Centrifugal pumps have proven to be reliable and commercially available devices for use in sCO_2 systems. This pump is a combined centrifugal pump and induction electric motor in a hermetically sealed unit. A rotor-impeller assembly is the sole moving part and is driven by the induction motor magnetic field. Since the motor and impeller are located inside a single canned assembly, shaft seals are not needed, and the pump is leak-free. The rotor is immersed in the working fluid, and the bearings are continuously lubricated by the same working fluid. As shown in Figure 2, and to prevent the overheating of the working fluid, an API 685 Plan 21-S Cooled External Circulation pump was selected. This plan removes a portion of the discharge flow and precools (in a sCO_2 to water) it before reintroducing it inside the rotor cavity to ensure that the sCO_2 retains sufficient viscosity to act as bearing lubricant.

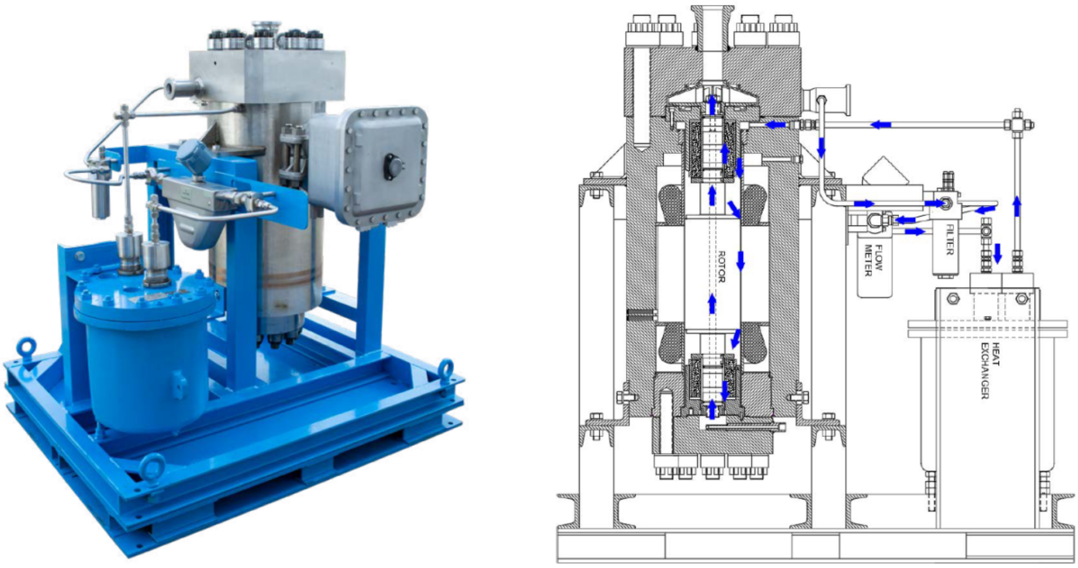

Figure 2. Circulation pump (left); circulation path (right)

The pump will be operated by a Variable Frequency Drive (VFD) that will control flow through the system. The pump can provide a flow rate up to 140 gallons/minute (8.8 L/s), corresponding to an sCO_2 flow of 7 kg/s and a pump head of 900 ft (275 m). Figure 3 shows pump curves at 60 and 73 Hz. The operational frequency is expected to be within the shown curves. These curves were calculated using a discharge orifice. Additional pump head is available if discharge orifice is not used during operation. The pump has a nominal power of 125 hp at a frequency of 60 Hz and nominal speed of 3450 rpm.

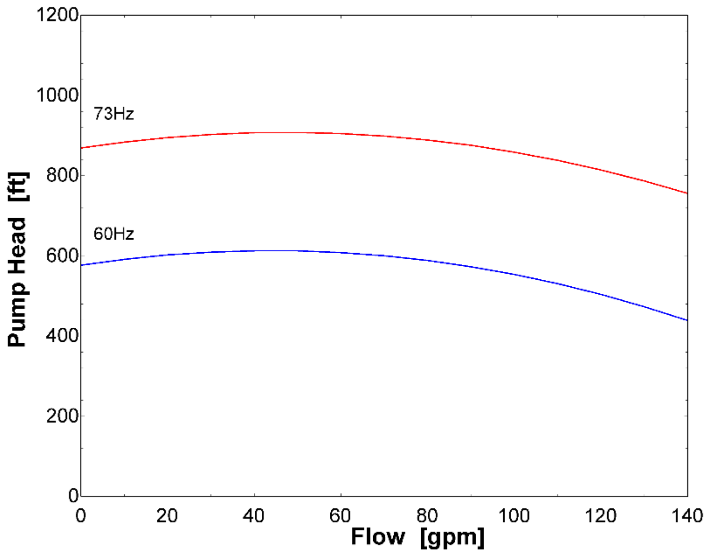

Figure 3. Pump curves at different operational frequencies

Air-to-sCO_2 Dry Cooler

Since CSP plants are usually in arid locations, dry cooling is an important aspect of the G3P3 sCO_2 cooling loop. The cooling duty of this system is accomplished by an air-to-sCO_2 printed circuit heat exchanger (PCHE) capable of sustaining internal pressures above 25 MPa. Austenitic stainless-steel 316 was the chosen alloy for the fabrication of this PCHE. To provide the 1.2 MW thermal duty, a centrifugal fan with a capacity of 64,000 cfm and a static pressure of 8 in water is attached to the PCHE. The power consumption for the fan motor is 125 hp. As of the date of this publication, the PCHE is in fabrication at Vacuum Process Engineering. A CAD model of the assembly is shown in Figure 4.

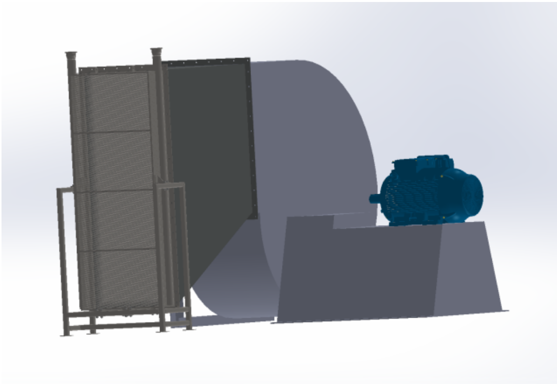

Image: VPE

Figure 4. CAD model of air-to-sCO_2 dry cooler

Recuperation System

The recuperation system is split into two recuperators to reduce the possibility of the occurrence of a pinch point and to reduce cost of a single recuperator made of expensive high-nickel alloys. The two heat exchangers are printed circuit heat exchangers (PCHE) and are identified by the main material of construction: stainless-steel and nickel-alloy.

- Stainless Steel Recuperator
    - 3 MW thermal duty
    - Austenitic stainless-steel 316 core construction
- Nickel Alloy Recuperator
    - 1 MW thermal duty
    - Inconel 617 core construction

The recuperation system is collocated with the PHX (

Figure 5) to moderate cost since the connections between the nickel alloy recuperator and the PHX will consist of Inconel 625 and Inconel 740H piping, which is expensive and not readily available.

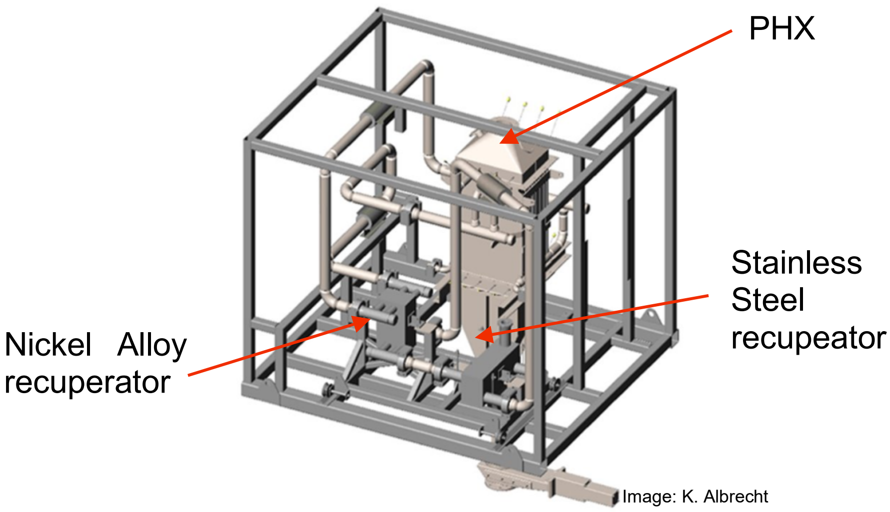

Figure 5. G3P3 PHX and recuperators skid

Other Components

Instrumentation System

The instrumentation system consists of control and monitoring equipment. The process and instrumentation diagram (P&ID, Figure 6) shows the instruments used in the system. Flowmeters in the main pipelines are Venturi flowmeters, but some Coriolis flowmeters are used in lines 1.5 NPS and below since commercial Coriolis flowmeters are available at pressure ratings that satisfy the system needs over 25 MPa. Temperature measurements are obtained via Resistance Temperature Detector (RTD) inserted via compression seal feedthroughs. Differential and absolute pressure measurements are performed via diaphragm pressure transducer/transmitter. Control valves are ball valves with electrical actuators.

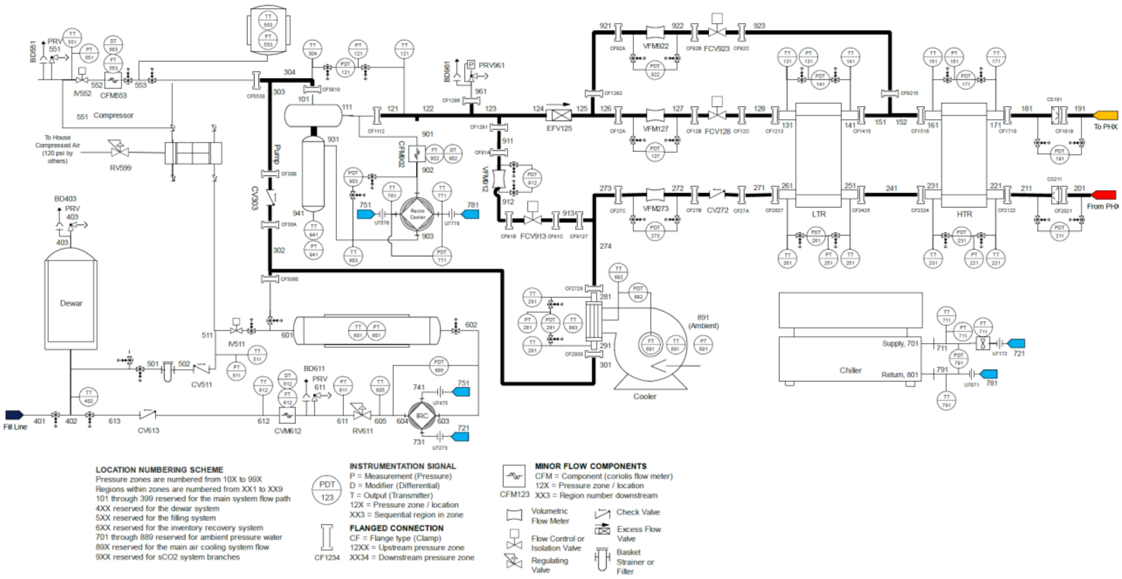

Figure 6. Process and Instrumentation Diagram

Piping and Connectors

Piping and connectors are designed to comply with ASME B31.1 Power Piping code. As shown in Table 3, the operating conditions can be met by austenitic stainless-steel 316. The pipe sizes range from 1.5 to 3 NPS and from schedules 160 to XXH. The pipes to and from the PHX to the recuperator as well as the corresponding connectors will be made of Inconel 625 (upcomer, PHX inlet) and Inconel 740H (downcomer, PHX outlet) and are not shown in Table 3.

Table 3. sCO_2 cooling loop operating and design conditions for pipe runs

sCO2 Skid Line List									
Line No.	Operating Conditions			Design Conditions		Hydrotest	Pipe Material	Insulation Material	Insulation Thickness
	[°F]	[psi]	[lbs/in^3]	[°F]	[psi]	[psi]			
sCO2-001	132	3524	0.029	152	4100	6150	A312 TP316	Cal-Sil	1"
sCO2-002	136	3756	0.029	156	4100	6150	A312 TP316	Cal-Sil	1"
sCO2-003	794	3713	0.007	913	4100	6150	A312 TP316	Cal-Sil	4"
sCO2-004	1067	3597	0.005	1200	4100	6150	A312 TP316	Cal-Sil	4"
sCO2-005	296	3553	0.015	340	4100	6150	A312 TP316	Cal-Sil	2.5"

G3P3 Layout

The G3P3 system is a tower system with storage bins built into the tower as shown in Figure 7a. The baseline layout contained the sCO_2 cooling loop on the third level. As shown in Figure 7b the sCO_2 will be split between the third and fourth levels by moving the recuperation system next to the PHX (fourth level) to minimize the amount of high-nickel alloy piping needed.

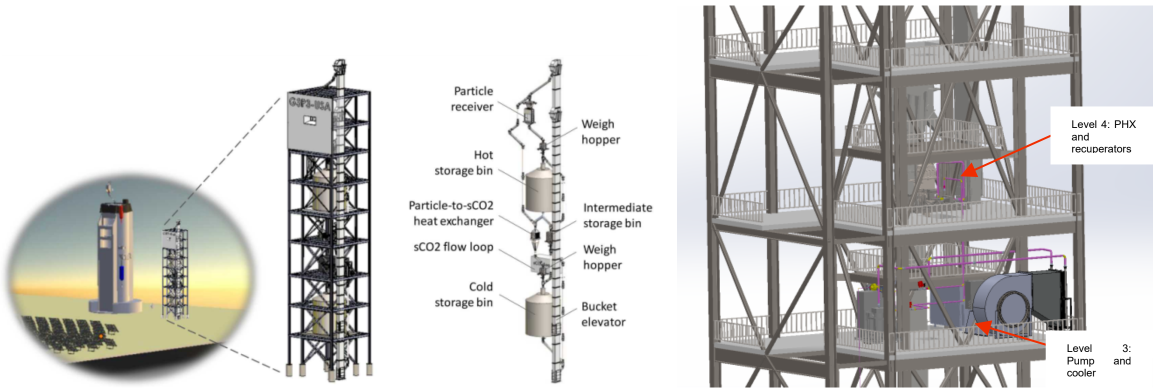

Figure 7. a. Left: Location and baseline design of the G3P3-USA system at the NSTTF[1]; b. Right: Location of sCO_2 loop on third and fourth level of G3P3 tower.

Conclusions

The G3P3 system is under construction at the National Solar Thermal Test Facility. A particle-to-sCO_2 system is being developed as part of G3P3 to prove the heat exchange between ceramic particles and sCO_2 at a 1 MW thermal scale. The status of the development and construction of the sCO_2 cooling loop are presented in this paper.

Data availability statement

Collected data was not utilized to generate conclusions on this work. The corresponding author can be contacted for any information related to this publication.

Underlying and related material

Previous published work by the author related to this system can be found under doi: 10.1115/1.4049289.

Author contributions

Francisco Alvarez supported the component design and integration within the G3P3 system and wrote this publication as a single author.

Competing interests

The author declares no competing interests.

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