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A PARTICLE/SCO2 HEAT EXCHANGER TESTBED AND REFERENCE CYCLE COST ANALYSIS

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ABSTRACT

The high-temperature particle – supercritical carbon dioxide (sCO2) Brayton power system is a promising option for concentrating solar power (CSP) plants to achieve SunShot metrics for high-temperature operation, efficiency, and cost. This system includes a falling particle receiver to collect solar thermal radiation, a dry-cooled sCO2 Brayton power block to produce electricity, and a particle to sCO2 heat exchanger to couple the previous two. While both falling particle receivers and sCO2 Brayton cycles have been demonstrated previously, a high temperature, high pressure particle/sCO2 heat exchanger has never before been demonstrated. Industry experience with similar heat exchangers is limited to lower pressures, lower temperatures, or alternative fluids such as steam. Sandia is partnering with three experienced heat exchanger manufacturers to develop and down-select several designs for the unit that achieves both high performance and low specific cost to retire risks associated with a solar thermal particle/sCO2 power system. This paper describes plans for the construction of a particle sCO2 heat exchanger testbed at Sandia operating above 700 °C and 20 MPa, with the ability to couple directly with a previously-developed falling particle receiver for on-sun testing at the National Solar Thermal Test Facility (NSTTF).

INTRODUCTION

The December 12th, 2015 agreement at the Conference of Parties (COP21) summit [1] has highlighted the importance of ongoing efforts in the United States (US) and internationally to expand the usage of renewable, carbon-free energies including solar power. The SunShot vision study from 2012 [2] has estimated that a 75% decrease in the cost of solar energy down to $0.06 per kilowatt-hour (kWh) could drive increased solar adoption from 2012 levels of less than 1% up to 14% by 2030. While this market penetration is an essential component in an “all of the above” strategy to tackle climate change [3] and limit global temperature rises to less than 2 degrees Celsius (°C), the envisioned 75% cost reductions require correspondingly aggressive investment in renewable energy technology research and development.

Concentrating solar power (CSP) plants have the greatest potential to quickly increase non-nuclear renewable electrical generation capacity in the US as compared to photovoltaic systems with increased efficiency and the potential for high-temperature thermal energy storage allowing for higher plant capacity factors. The Ivanpah Generating System is a recent implementation of CSP at 377 MWe net capacity at a temperature of 565 °C and an efficiency of almost 29% [4]. However a number of trade-offs were necessary to make this plant potentially viable, including the use of a conventional steam Rankine power conversion, a back-up natural gas turbine for start-up and low-sun periods rather than solar thermal storage, and $1.6 billion in federal loan guarantees.

In order to achieve 75% cost reductions from this current state-of-the-art, the Department of Energy (DOE) office of Energy Efficiency and Renewable Energy (EERE) has established power cycle performance targets of a net thermal to electric conversion efficiency higher than 50% with dry cooling to ambient air at 40 °C, with a power block system cost of less than 900 $/kWe in order to meet the overall levelized cost of electricity (LCOE) goal of 6 ¢/kWh. Previous studies [5]–[7] have suggested that this combination of targets is very aggressive given the current uncertainty with key power block components, including the primary heat exchanger and high-temperature turbomachinery support systems.

Our work described here will address these uncertainties as they relate to a particle/sCO2 primary heat exchanger, highlighted in Figure 1 as part of the full CSP sCO2 Brayton system, in collaboration with three vendor partners, Babcock and Wilcox, Solex Thermal Sciences, and Vacuum Process Engineering. We will develop several alternative heat exchanger designs for evaluation in FY16, as well as plans for a high-temperature sCO2 component test bed capable of operating at up to 700 °C and 20 MPa. In future years at least one of these heat exchanger designs will be prototyped and tested using the high-temperature sCO2 system, with eventual integration with the falling particle solar receiver already constructed at the National Solar Thermal Test Facility (NSTTF) located at Sandia National Labs.

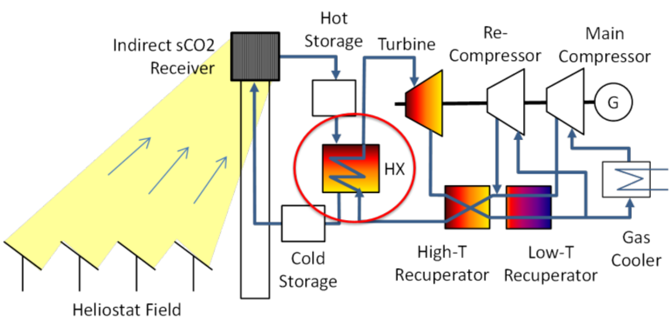


Figure 1: A recompression sCO2 Brayton CSP plant layout with the particle/sCO2 primary heat exchanger highlighted.

SCO2 CYCLE LAYOUT OPTIONS

A significant challenge in reducing the uncertainties related to the particle/sCO2 primary heat exchanger is the wide array of sCO2 power cycle layouts possible with operating conditions ranging significantly in both pressure and temperature. While the fundamental questions related to high-temperature pressure containment, particle-to-wall heat transfer, and fatigue life are not expected to change with operating conditions past a certain point, component cost and “unknown unknowns” can only be addressed with a device operating in as realistic a condition as possible. It’s therefore necessary to identify a maximum set of common operating conditions that can practically be achieved by stretching current material and manufacturing capabilities.

Literature studies on various cycle layouts **[5], [7]–[22]** have considered several options, including simple, recuperated, recompression, combined, partial cooling, and cascaded cycles, among others, with pressures ranging from 15 to 35 MPa and temperatures from 300 to 1500 °C as summarized in Table **1**. Concentrating solar power alone ranges from 500 to 1000 °C and 20 to 35 MPa. While thermodynamic paper studies can easily suggest the promise of these high temperatures and pressures, current material capabilities put significant limits on cycle operating parameters as shown in Figure 2.

Table 1: sCO2 Brayton applications, adapted from [23].

Application	Size / MWe	Temp / °C	Pressure / MPa
Nuclear	10-300	350-700	20-35
Fossil (Indirect)	300-600	550-900	15-35
Fossil (Direct)	300-600	1100-1500	35
Solar	10-100	500-1000	20-35
Shipboard	<10-10	200-300	15-25
Waste Heat	1-10	<230-650	15-35
Geothermal	1-50	100-300	15

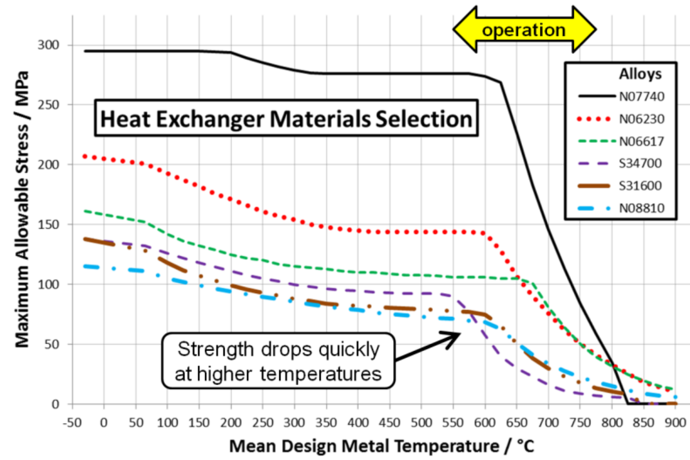


Figure 2: Material strength behavior at high temperatures.[24]

Using available nickel alloys operating conditions of 20 MPa and 700 °C were selected as the logical next step to demonstrate a particle/sCO2 primary heat exchanger in order to retire the critical risks of high-temperature pressure containment in an abrasive environment, effective particle-to-wall heat transfer, fatigue lifetime, and expected cost. These uncertainties can be understood now and the results can readily transfer to future demonstrations using advanced alloys or operating at larger power scales.

PARTICLE/SCO2 HEAT EXCHANGER TESTBED

A particle/sCO2 heat exchanger test bed is necessary to advance the technology from a technology readiness level (TRL) of 4 to TRL 6 by demonstrating a prototype device in the relevant environment, including key operating conditions of 20 MPa and 700 C. Previous work on fundamental particulate heat transfer and falling particle receivers **[25]–[32]** and industrial experience have demonstrated key technology elements of the particle/sCO2 heat exchanger equivalent to laboratory-scale testing of similar equipment in similar environments that aren’t yet completely relevant to the expected operation.

SCO2 flow loops exists at several institutions **[11], [33]–[37]** for testing individual components and full system performance, however one does not currently exist to meet the high temperature operating conditions and compact size needed for on-tower operation of a particle/sCO2 heat exchanger at the National Solar Thermal Test Facility (NSTTF) power tower coupled with an existing falling particle receiver shown in Figure 3. Balancing the operating temperature and pressure required with the available tower elevator space, material constraints, and off-the-shelf sCO2 pump options a preliminary 100 kWth particle/sCO2 heat exchanger prototype specification was developed for sizing the test loop, with key parameters shown in Table 2.

Table 2: Preliminary particle/sCO2 heat exchanger requirements.

PERFORMANCE OF ONE UNIT					
		HOT SIDE		COLD SIDE	
STREAM NAME		PARTICLES		SCO2	
FLUID FLOW RATE (TOTAL)	kg/s	0.41		0.53	
TEMPERATURE (IN/OUT)	°C	775	570.	550.	700.
PRESSURE (IN)	MPa	0.101		20.0	
PRESSURE DROP ALLOW.	kPa	N/A		200	
FOULING RESISTANCE	m^2-K/W	0.0 (nil)		0.000176	
HEAT EXCHANGED	100	kW			

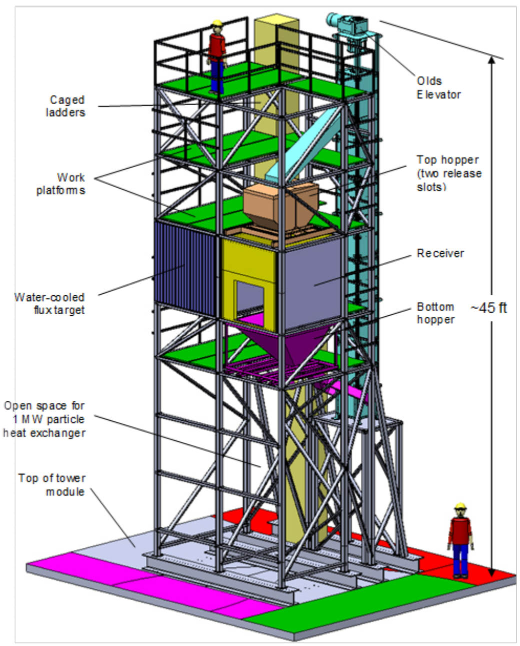
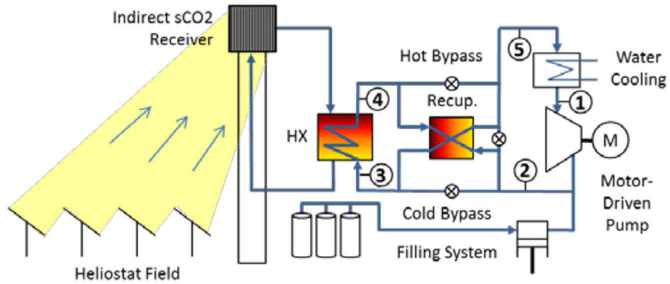


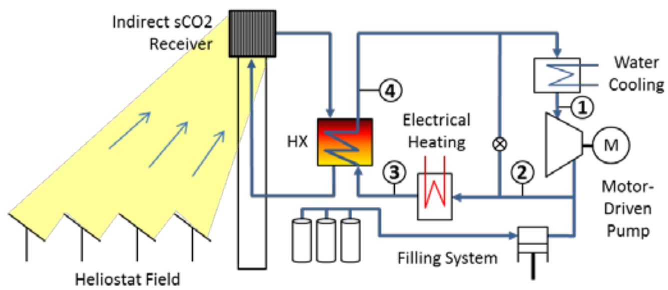
Figure 3: The Sandia falling particle receiver prototype.

In order to test the required performance of the heat exchanger prototype the sCO2 flow loop must be capable of delivering at least 0.75 kg/s of CO2 at 20 MPa and a temperature of 550 °C. Two alternative flow systems are being pursued as shown in Figure 4 and Figure 5. The first provides the greatest relevance to sCO2 power cycles, featuring a recuperator and compressor but operating at a single pressure to reduce the cost, lead-time, and size of the compressor. The second contingency design is being explored to mitigate cost and lead-time risks associated with the recuperator and compressor, but adds a large electrical pre-heater and significantly increases the size of the cooler.



State	1	2	3	4	5
T / °C	149	152	550.	700.	287.
P / MPa	19.4	20.2	20.0	19.8	19.6

Figure 4: The primary particle/sCO2 test bed design.



State	1	2	3	4
T / °C	37.8	38.4	550.	700.
P / MPa	19.6	20.2	20.0	19.8

Figure 5: The alternative particle/sCO2 test bed design.

For a 1 kg/s sCO2 flow loop, carbon dioxide cylinders, medium-temperature piping, reciprocating booster pumps for filling, and water coolers are all available from multiple vendors and are not seen as a significant project risk in terms of cost, size, or lead-time. Cost and schedule risks for the primary particle/sCO2 heat exchanger, the main component of interest, are being mitigated through partnership with multiple leading vendors in the field of heat exchanger design. The recuperator, pump, and high temperature piping in the primary design however are potential risks as there are few vendors capable of producing equipment suitable for sCO2 applications.

To mitigate the lead-time risk in the primary design, the alternate design uses electrical heating and a larger cooler and a low-temperature pump operating condition in place of the recuperator and medium-temperature pump. These components can be fabricated by a wider variety of vendors. The trade-off for this alternative is that these components will likely have a higher cost and are a further departure from the components in a sCO2 cycle loop compared with the primary design.

The high temperature piping connecting between the particle/sCO2 heat exchanger and downstream system components is expected to be a significant challenge as currently 1 in SCH 160 pipe fabricated from Inconel 617 (UNS N06617) is the only available option under American Society of Mechanical Engineers (ASME) B31.1 code section 104.1.2 strength requirements at 700 °C as shown in Table 3 and Figure 6. Inconel 800H (UNS N08810) and 316L austenitic stainless steel (UNS S31603) may also be able to meet B31.1 requirements using thicker pipe cross sections and/or smaller pipe diameters, but becomes increasingly impractical with any transient increase in temperature.

Table 3: Pressure-induced stress in various pipe forms based on ASME B31.1 code section 104.1.2. [38]

NPS	SCH	P	SE
in	#	MPa	MPa
½	160	20.0	58.7
¾	160	20.0	62.0
1	160	20.0	66.6

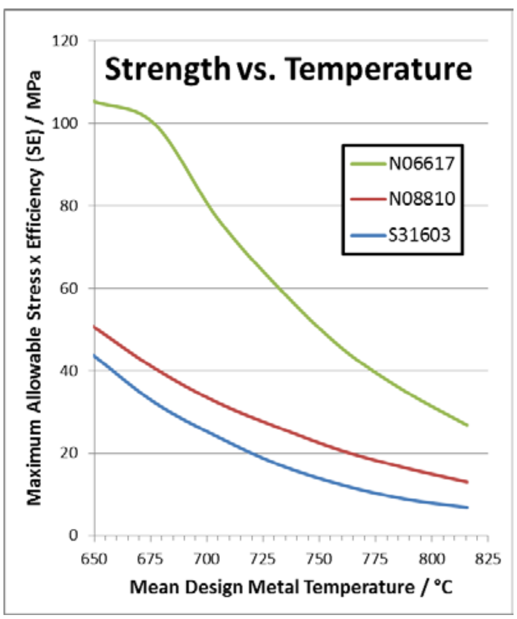


Figure 6: A plot of maximum allowable stress – joint efficiency product versus temperature. [38]

CONCLUSION

This project represents the last step required to complete a suite of independent sub-component developments aimed at advancing their technology readiness level (TRL) in preparation for an integrated solarized sCO2 Brayton cycle demonstration system. By the end of FY18 Sandia will have the necessary concentrating solar power tower, falling particle receiver, particle/sCO2 heat exchanger, and sCO2 Brayton cycle equipment to demonstrate this integrated system at a megawatt-scale.

Work is ongoing as part of this project in FY16 to complete a reference cycle cost analysis, develop three competing particle/sCO2 heat exchanger designs, and to complete design and begin procurement of the sCO2 flow loop required to test the particle/sCO2 heat exchanger. The preliminary design considerations for the latter two efforts have been described in this paper and design reviews are planned for July of 2016.

The reference cycle cost analysis will be completed earlier by April of 2016 in order to develop improved cost targets and other evaluation criteria for the particle/sCO2 heat exchanger. This analysis has proved challenging due to the need to protect information around individual equipment vendors' quotes from revelation to their direct competitors. However at the same time all vendors, researchers, and customers need an understanding of realistic cost targets to spur innovation in designs and manufacturing approaches where they are needed most. We hope to provide this guidance to the research community in our future publications.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
°C	degrees Celsius
CSP	Concentrating solar power
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
kWh	kilowatt-hour
LCOE	levelized cost of electricity
MPa	Megapascals
NSTTF	National Solar Thermal Test Facility
NPS	Nominal Pipe Size or Nominal Diameter
P	Pressure
sCO2	supercritical carbon dioxide
SCH	Pipe schedule (thickness)
SE	Maximum allowable stress and joint efficiency product
TRL	technology readiness level
US	United States

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