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Testing Platform and Commercialization Plan for Heat Exchanging Systems for S-CO2 Power Cycles

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Abstract

Supercritical Carbon Dioxide Closed Brayton Cycle (S-CO2 CBC) systems have the potential to convert thermal energy to electricity at efficiency significantly higher than traditional steam Rankine cycles. The primary difference in the Brayton cycle that enables higher efficiency is the availability of a useful temperature difference between the high temperature, low pressure flow exiting the turbine, and the low temperature, high pressure flow exiting the compressor. In the S-CO2 CBC cycle, this temperature difference drives heat transfer through recuperation in heat exchangers. Overall cycle energy conversion efficiency increases as the extent of recuperation increases.

The platform, once commissioned, can test many types of heat exchangers to investigate performance characteristics and to select which application they will be best suited for. Characterizing these heat exchangers will facilitate understanding how they scale. Plant economics will be a major factor in the selection of these heat exchangers. It has been identified that at this time, up to 90% of the cost of the S-CO2 Brayton Cycle will be in the heat exchangers. This percentage assumes the use of printed circuit heat exchangers. Although these heat exchanger are approximately 98% efficient and a relatively high cost, the use of a lower efficiency and less costly heat exchanger may make this S-CO2 technology more attractive for a path forward commercialization.

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NOMENCLATURE

ASTM	American Society for Testing and Materials
°C	Degrees Centigrade
CO_2	Carbon Dioxide
CBC	Closed Loop Brayton Cycle
DOE	U.S. Department of Energy
GEN IV	Generation IV
NEUP	Nuclear Energy University Programs
PCHE	Printed Circuit Heat Exchanger
S-CO_2	Supercritical Carbon Dioxide
SNL	Sandia National Laboratories

1. INTRODUCTION

Supercritical Carbon Dioxide Closed Brayton Cycle (S-CO2 CBC) systems have the potential to convert thermal energy to electricity at efficiency significantly higher than traditional steam Rankine cycles. The primary difference in the Brayton cycle that enables higher efficiency is the availability of a useful temperature difference between the high temperature, low pressure flow exiting the turbine, and the low temperature, high pressure flow exiting the compressor. In the S-CO2 CBC cycle, this temperature difference drives heat transfer through recuperation in heat exchangers. Overall cycle energy conversion efficiency increases as the extent of recuperation increases.

Ideally, the low pressure flow temperature exiting the last heat exchanger before entering the compressor will equal the high pressure flow temperature exiting the compressor. Both heat exchanger capital costs and power plant operating income rise as this ideal is approached. The capital costs are considered in relation to their effect on profit from a S-CO2 CBC power plant selling electricity. Sandia is currently designing a heat exchanger test platform to support research and development of heat exchanger technology for S-CO2 power cycles. This platform will facilitate investigating performance characteristics of various new heat exchanger technologies, such as pressure drop, efficiency, failure modes, etc. The platform will be able to accommodate many types of exchangers of different physical sizes and flow rates. The purpose of this testing is to identify the correct heat exchanger for the many various S-CO2 applications. Testing will be a focal point of the research and commercialization plan for Sandia to identify a path forward to develop a 10MW simple recuperated Brayton cycle.

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2. EXPERIMENTAL SCALING OF S-CO_2 BRAYTON CYCLE

Sandia National Laboratories has conducted S-CO2 testing on-site using small scale loops in order to provide a test bed for the development of supporting technologies that are necessary to large scale, commercial operations. The on-site demonstration loops (~1 MWth) are considered robust enough to address fundamental control and stability issues associated with a commercial system yet small enough to permit multi-year funding as part of the current DOE Gen IV Energy Conversion research budget. The main disadvantage of a small test loop involves the scaling of the turbomachinery. High rotational speeds associated with the 1 MWth loop as well as bearing, seal, and motor approaches may not be representative of a large scale system. While these issues are not predicted to detract from performance in a large system, evaluation of them is important to assure there are no important uncertainties when expanding to a commercial system.

A second, slightly larger demonstration loop is also located at Sandia. This loop was purchased by Sandia National Laboratories and is consistently used for experimental operations. Barber Nichols fabricated both the Sandia on-site loops. Collaboration between Sandia and Barber Nichols has demonstrated potential future cooperation between national laboratories and private industry as research into S-CO2 power conversion systems continues.

3. TESTING PLATFORM

Sandia is currently designing a heat exchanger test platform to support research and development of heat exchanger technology for S-CO2 power cycles. This platform will facilitate investigating performance characteristics of various new heat exchanger technologies, such as pressure drop, efficiency, failure modes, etc. The platform will be able to accommodate many types of exchangers of different physical sizes and flow rates. The purpose of this testing is to identify the correct heat exchanger for the many various S-CO2 applications. Testing will be a focal point of the research and commercialization plan for Sandia to identify a path forward to develop a 10MW simple recuperated Brayton cycle.

Sandia's research heat exchanger platform has the potential to test heat exchangers ranging in size from 1'x1'x1' all the way to 5'x5'x5' to test performance characteristics of the many different types of heat exchangers. The contingency for the heat exchangers is they must have Grayloc 3GR25 commercially available connections that can be bolted to the test rig. This test loop can be tested in multiple ways, these ways include; water to CO2, propylene glycol to CO2, and CO2 to CO2. The test rig can operate in liquid, gas and supercritical state.

The basic requirements of the inputs to a S-CO2 Brayton cycle recuperator for a variety of different 1 MWe cycle layouts are shown in Table 3-1, with a rough diagram shown as Figure 3-1. The key elements of this layout for heat exchanger testing include the differential and absolute pressure transducers, as well as inlet and outlet temperature measurements for each stream. Temperature should be measured using RTD probes for high stability and accuracy, as well as a high-accuracy differential pressure transducer to accurately measure the pressure drop through the heat exchanger. Coriolis flow meters would be preferred at each stream inlet for their high accuracy as well as the ability to read the inlet density of the stream which is more accurate in determining the flow state than temperature. The shut-off and purge valves on the pressure measurement lines will allow for pressure transducers to be isolated and calibrated in-place or taken from the loop for calibration without venting inventory. Bypass valves for each stream entering the heat exchanger under test will allow for heat exchangers designed for un-equal flow rates to be tested, and in combination with the flanges would allow for pre-coolers and low-temperature intermediate heat exchangers to be tested in the same setup. The recuperator will need to transfer up to 3 times the thermal input into the cycle, so the heater and fluid cooler will need to be sized as according to the design of a simple recuperated Brayton cycle in order to test a recuperator at full load. Pre-coolers, intermediate heat exchangers, and heat exchangers designed for other Brayton cycle layouts will likely individually transfer less heat than a simple Brayton cycle would require.

Table 3-1. The primary inlet requirements for a Brayton cycle recuperator.

	Stream A	Stream B
Temperature [K]	275 to 340	450 to 600
Pressure [MPa]	12 to 20	7 to 10
(1 MWe) Mass Flow Rate [kg/s]	0 to 20	0 to 20

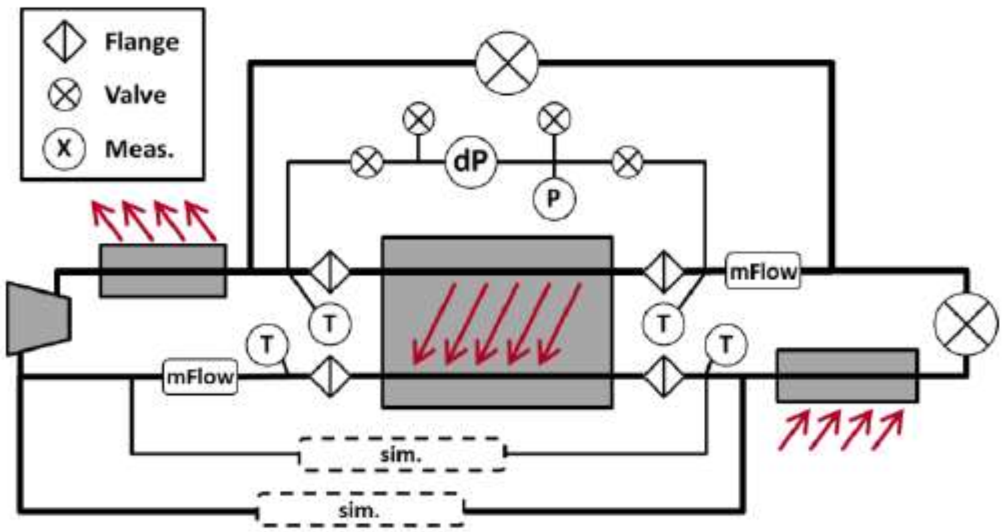

Figure 3-1. A diagram of a possible configuration of the heat exchanger test loop. Note that this layout is very similar to the S-CO2 compression test loop, and the 1 MW S-CO2 Brayton loop using just one TAC unit. The flanges and bypass valves would allow both recuperators and pre-coolers to be tested.

4. PATH FORWARD TO COMMERCIALIZATION

In order to obtain a path forward for commercialization of large heat exchangers we believe that several issues need to be resolved before anxious commercialization. The first issue is the potential for corrosion with Stainless Steel 316 and diffusion bonding, we found intergrannular corrosion within our SS316 sch. 160 pipe almost a year ago. We anticipate to pave the way to commercialization by identifying the problems with possible corrosion and with the selection of high temperature materials selection.

5. DIFFUSION BONDED COUPONS

Sandia National Laboratories (SNL) is developing a S-CO2 system that requires various heat exchangers. The preferred heat exchanger design is one that uses microchannels to conduct each of the two streams in the heat exchanger.

The first phase SNL has chosen to do is have their selected supplier prepare stacks of 0.125" thick SS 316L shims, sandwiched between suitably thick endplates, as shown in Figure 5-1. The shims and end plates will be nominally 3" square.

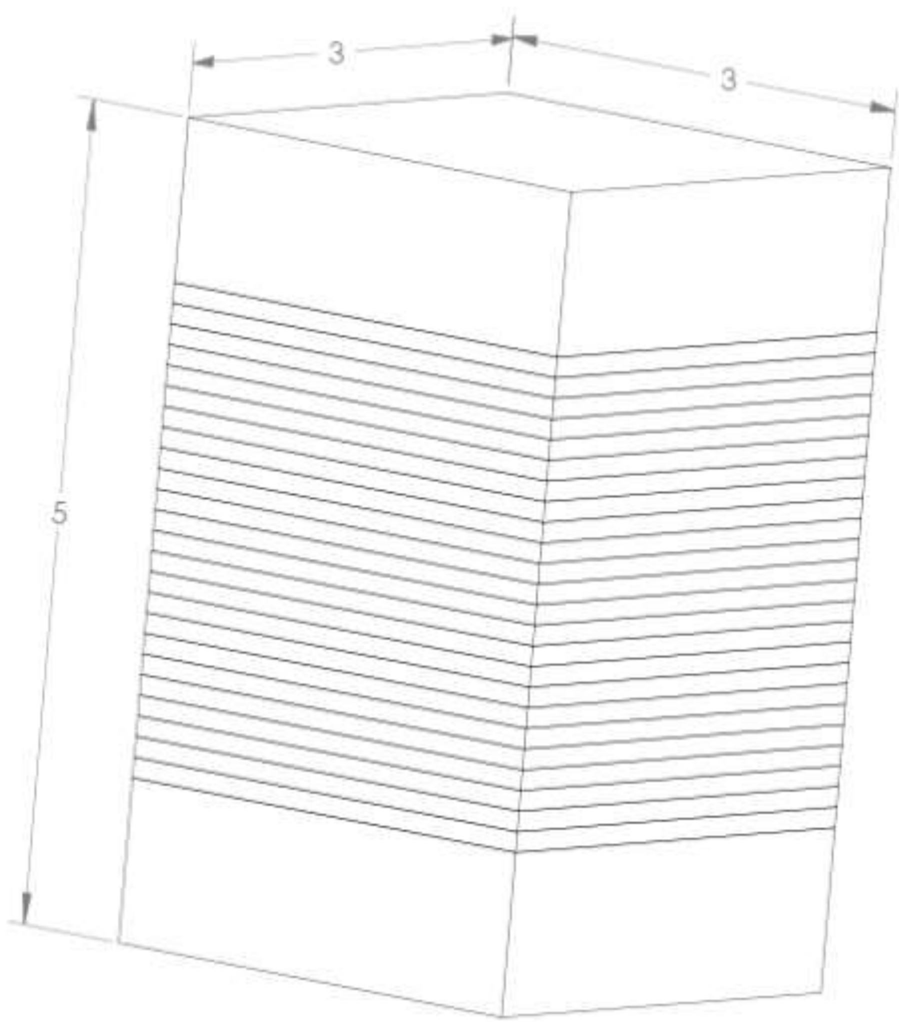

Figure 5-1. SNL's cube of bonded SS 316L for establishing bonding parameters.

These stacks will be bonded and then appropriately sized ASTM tensile specimens will be cut from each bonded stack (approximately 9 samples per stack). SNL will tensile test these specimens and convey the results to Sandias selected contractor. If the resulting yield strength and/or ultimate tensile strength are too low, the selected contractor will modify the bonding parameters and prepare additional stacks. It is anticipated that at least three (3) of these stacks will be required to establish the proper bonding parameters.

Sandia's selected supplier is supplying all materials, fabricate the shims and endplates, and perform any necessary material treatment (e.g. grinding, plating) for the selected bonding process. We will then stack the bonded the cubes, recording all pertinent process information (e.g. bonding temperature, bonding pressure, time at temperature and pressure). Sandia's contractor will be responsible for the design and fabrication of all tooling for the bonding process. Upon completion of each stack, we will prepare tensile specimens, per ASTM E8, and provide these specimens to SNL for testing.

6. RESULTS OF DIFFUSION BONDED SAMPLES

Diffusion bonded samples are currently being fabricated and then tested. The results will be known in March 2013 and will be shared in the presentation portion of the ASME Turbo Expo.

7. HEAT EXCHANGER MATERIALS CONSIDERATIONS

Sandia just recently performed a literature review regarding corrosion issues for a molten sodium to S-CO2 intermediate heat exchanger, concluding primarily pure, dry S-CO2 at temperatures below 500 °C is not a concern for the stainless steels and high-nickel alloys proposed for S-CO2 Brayton cycle heat exchangers, but that above 600 °C and with water contamination of ppm levels S-CO2 becomes much more corrosive to ferritic-martensitic steel, Ferritic steel with more than 20% Cr, austenitic steel, and nickel alloys, in that order. There also appeared to be a significant difference between corrosion of un-strained coupons in the laboratory and components under stress, and no corrosion information was available on diffusion-bonded materials. Literature gaps in stress-corrosion research and corrosion of diffusion-bonded materials need to be addressed to gain more confidence in the long-term reliability of S-CO2 Brayton cycle heat exchangers, especially where printed-circuit heat exchangers (PCHE) are used.

- SNL is working independently to investigate the strength of 316 SS diffusion bonds
    - Baseline bond characterization
    - Tensile testing at room and elevated temperature and creep testing
    - Same mechanical testing after soaking in high-temp S-CO2
    - Same mechanical testing after soaking in the Brayton loop

- SNL is coordinating with UW-Madison to address these gaps in literature through a NEUP proposal
    - Static corrosion testing in 99.999% pure S-CO2 of T22 and T91 ferritc steel (300 to 400 °C), Incoloy 800H and 347 SS (400 to 600 °C) and Inconel 740 and SiC (600 to 750 °C)
    - Static corrosion testing of diffusion bonded samples (347 SS, Incoloy 800H, Inconel 740)
    - Stress-corrosion cracking in S-CO2 C-ring tests per ASTM (T-91, 347 SS, Inconel 740, diffusion-bonded samples)
    - Corrosion testing with known corrosion antagonists and inhibitors (water, Cl-, vs. CO, H, hydrocarbons)

8. HEAT EXCHANGER OPTIONS

Hesselgreaves and Li et. al. provide good summaries of existing compact heat exchanger options that may be applicable as a S-CO2 Brayton cycle recuperator. Table 8-1 lists useful design information for a variety of compact heat exchangers from these two sources, with rough cost estimates given based on the heat exchanger UA and data from Hesselgreaves. Note that Dostal reports Heatric™, currently the only manufacturer of PCHEs, uses a range of 30 to 50 $/kg rather than a value based on UA for their heat exchangers since there can be considerable variation in the channel layout on PCHE plates to vary the UA without affecting the fabrication process. Using these numbers, a 1 to 3 MW/K recuperator for a S-CO2 Brayton cycle would be something around 3.5 to 10 M$.

Table 8-1. A comparison of several compact heat exchanger characteristics with data from Hesselgreaves and Li et al.

CHX Type	P_{max} [MPa]	T [°C]	β [m2/m3]	dh [mm]	Cost [$/(W/K)]
Ceramic HE	1	1300 to 1900	-	-	-
Spiral HE	0.6 to 2.5	200 to 540	-	10 to 50	-
PHE (Gasketed)	2.5 to 3.5	-35 to 250	120 to 660	2 to 10	0.05
PHE (Welded)*	4	-50 to 350	120 to 660	2 to 10	0.25
PHE (Brazed)	4.5	-195 to 225	120 to 660	2 to 10	-
PHE (Compabloc)	4.5	350	120 to 660	2 to 10	-
PHE (Hybrid)	8	900	-	-	-
Shell & Plate	20	950	-	-	-
PFHE (Brazed)	9 to 12	Cyro** to 700	800 to 1,500	1 to 2	1***
PFHE (Diff.-Bond)	20 to 62	Up to 800	700 to 800	1 to 2	-
CBHE (Marbond)	40	-200 to 900	Up to 10,000	0.33 to 1	-
PCHE	50 to 100	-200 to 900	200 to 5,000	0.5 to 3	3****

* Also known as an AlfaRex PHE.
** "Cryogenic temperatures" not specified by Hesselgreaves.
***For steel; aluminum is about 0.33, titanium is about 1.8.
****For high-pressure steel; about 0.75 for low and medium-pressure service.

9. CONCLUSION

Sandia is currently undergoing a trade study between various types of heat exchangers and validating performance characteristics of each one. Sandia believes after receiving these in depth quotes from several companies and after testing we believe we can identify a cost per lb for each and correctly identify a way forward to a commercialization plan for the selected heat exchanger. Although there may be an already identified heat exchanger such as the PCHE, the diffusion bonded samples underway will investigate these parameters during the diffusion bonding practice and make sure they are suitable for the scaling up consideration due to temperature, corrosion and cost.

10. ACKNOWLEDGEMENTS

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