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Design, Fabrication and Testing of Novel Compact Recuperators for the Supercritical Carbon Dioxide Brayton Power Cycle

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ABSTRACT

A recuperated supercritical carbon dioxide (sCO_2) Brayton power cycle is a cost-effective and clean power generation system offering improved efficiency, reduction in emissions and water use, and adaptability to a variety of heat sources such as nuclear, gas, coal, concentrated solar, and biomass. The properties of sCO_2, as the working fluid, and high operational pressure (i.e. ~240 bar) and turbine inlet temperature (i.e. ~700°C) enable high cycle efficiency approaching 50% and allow for very compact turbomachinery. Achieving this high efficiency and profitability significantly depends on the performance and cost of the recuperator heat exchangers at these operating conditions.

This presentation will focus on two prototype recuperators designed for the sCO_2 Brayton power cycle with inlet temperature of 550°C and inlet pressure of 255 bar. The recuperators were designed based on the novel Stacked-Sheet Heat Exchanger (SSHX) concept. This compact recuperator design allows for the fabrication of cost-effective and high-performance recuperators. The SSHX concept will be reviewed along with its impact on the material selection and use of advanced manufacturing technologies.

The two recuperators made using different advanced manufacturing technologies and different materials were tested in Thar Energy's sCO_2 Brayton power cycle heat exchanger test facility. The reconfigurable test loop operates as a simple recuperated cycle with a pump instead of a compressor and a pressure reducing valve in place of the turbine expander. The test loop can accommodate test pressures up to 255 bar and temperatures up to 700°C. The sCO_2 mass flow rate can be adjusted up to 10 kg/min.

Recuperator tests were conducted over a range of temperatures (i.e. 200-550°C) and pressures (i.e.150-250 bar). Thermal and hydraulic performance data, to be reviewed and discussed, will include heat transfer, effectiveness, heat transfer coefficient, approach temperature and pressure drop. The talk will conclude with a review of the thermal performance test data and its comparison to the prediction of the thermal design models used to design the heat exchangers.

INTRODUCTION

The supercritical carbon dioxide (sCO_2) Brayton power cycle is adaptable to a variety of heat sources and has higher cycle efficiency compared to traditional power cycles. As such, it is being considered for multiple power generation applications such as waste heat recovery, fossil, concentrated solar power, geothermal, and nuclear. A key determinant on power cycle efficiency and profitability is the recuperator heat exchanger (HX) performance and cost. [1]

Thar Energy, LLC (Thar), with funding support from U.S. DOE NETL [2], has worked to evaluate, advance, and demonstrate recuperator design concepts, materials, and fabrication methods. The program's focus has been on building cost effective recuperators at the 46 MWt scale. During this program, Thar, in partnership with Southwest Research Institute, bench-marked commercial state-of-art recuperators against each other and with several novel HX recuperator concepts. Additionally, Thar evaluated a full range of manufacturing methods to determine their most cost-effective use and fabrication tolerance limitations. [3]

High temperature recuperator performance criteria were developed as a basis to evaluate both state-of-the-art recuperators and new recuperator concepts. Each concept was evaluated to the Supercritical Transformational Electric Power (STEP) performance criteria [4] and shown in Table 1. The criteria include thermal effectiveness, pressure loss, operating temperature and pressure conditions, size, and cost. Practical considerations such as operational lifetime and maintenance are also considered.

Stacked-Sheet Heat Exchanger (SSHX) Recuperator

Based on the performance criteria, the novel recuperator concept down selected for prototype fabrication and testing is named the Stacked-Sheet Heat Exchanger (SSHX). The SSHX as its name suggests, is composed of a stack of aligned and bonded perforated metal sheets, Figure 1. When used to design a sCO_2 recuperator, the sheets are stacked and aligned together such that the holes form flow passages for both the low-pressure, hot stream and the high-pressure, cold stream. This allows the separated fluids to transfer heat through the solid metal that separates them. If the flow passages are circular, the stacked sheets end up forming, in essence, the inner diameter of microtubes. The sheets are permanently held together by brazing or diffusion bonding.

Table 1. S.T.E.P. Recuperator Criteria [4]

Criteria	S.T.E.P. Target
Thermal Capacity	45.9 MWt
Thermal Effectiveness	97%
Pressure Loss	$\Delta P_h < 1.5\%$ $\Delta P_c < 0.6\%$
Temperature Limit	577°C
Differential Pressure	152 bar
Life	30,000 hr
Cost	< $100 / kWt
Package Dimensions	8.8 x 3.6 x 2.6 m

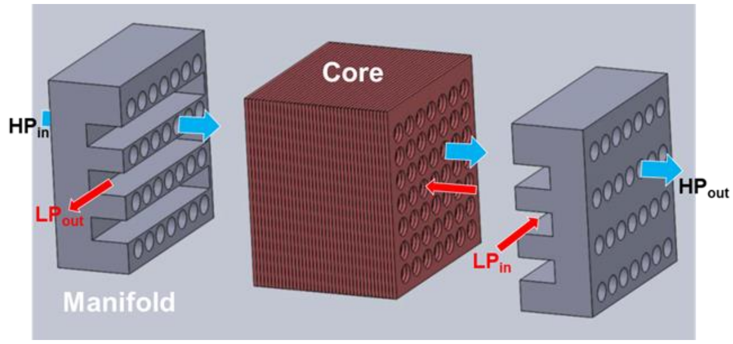
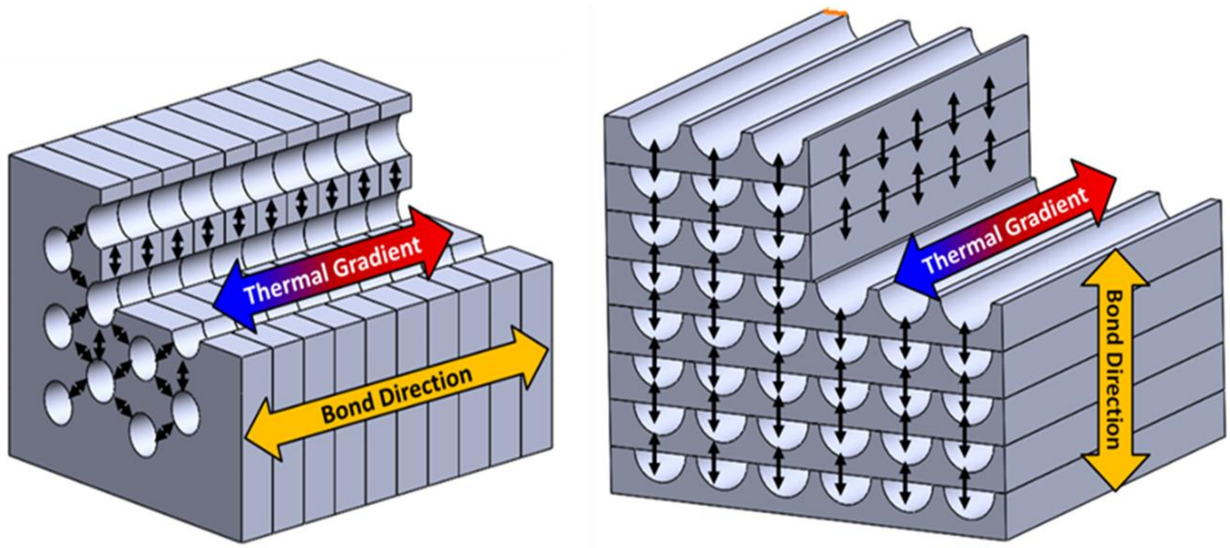


Figure 1. Stacked Sheet Recuperator Concept

In addition to the HX core, manifolds and headers are required. The manifolds are used to distribute the hot and cold flows into their respective passages, Figure 1. Headers are used to connect the separated hot and cold flows to the process piping.

One of the benefits of the SSHX concept is the bond between sheets is parallel to the mechanical stresses and perpendicular to the thermal gradient stresses, Figure 2a. This improves the structural integrity and thermal compliance of the SSHX recuperator, as compared to the state-of-the-art printed circuit HX, whose bonds are oriented at 90°, Figure 2b.



a) Stacked-Sheet HX **b) Printed-Circuit HX**

Figure 2. SSHX and Printed-Circuit HX mechanical and thermal stress distribution with respect to bond direction.

Recuperator pressure drop and thermal capacity for each flow streams can be adjusted independently, by setting the number of passages, their size and spacing for each flow stream. Like most compact HXs, surface density and the heat transfer coefficient improve as passage size and passage spacing decreases, as does the HX size. However, manufacturing tolerances, for hole size, spacing and sheet alignment ultimately dictate how small and close the passages can be, as does corrosion and fouling allowances and assumptions of bonding effectiveness per ASME Boiler and Pressure Vessel codes.

The full range of manufacturing methods, both subtractive and additive, were evaluated to determine fabrication tolerance and cost. Fabrication features includes surface roughness, passage geometry and stack up tolerances for a given metal and given sheet metal thickness. For the same size recuperator, manufacturing methods that can perforate thicker sheets have the advantage of fewer sheets and fewer bonds. This lowers the cost of bonding if brazing is the selected method of joining.

Two prototypes were made based on the SSHX design. The first prototype recuperator was designed based on additive manufacturing/3D printing/Direct laser metal sintering and was made out of Inconel 625 (3D-SSHX). Reasons included that the cost of 3D printing had decreased during the course of this project, and the quality of the parts produced, using Inconel 625, had increased. 3D printed parts also enabled a tighter part tolerance that allowed for a significantly more compact HX design to be evaluated. Also, costs for fabricating a prototype were affordable, a finding that surprised the team as 3D printing costs, just a few years earlier, were out of reach for this project.

Additionally, given the HX's compact design, the cost differential for producing a part using 316 stainless steel or Inconel 625 was determined to be acceptable. As such, the 3D-SSHX prototype recuperator was fabricated using Inconel 625 because of its superior mechanical and corrosion resistant properties. A sweet spot was identified balancing high thermal effectiveness and low pressure drop, with minimum recuperator size, weight, and cost.

For the second prototype recuperator, both the core and manifold sections were fabricated using laser cut, stainless steel 347H sheets (Laser-SSHX). As the name implies, the Laser-SSHX uses metal sheets where the hole pattern is cut using a laser. This Laser-SSHX prototype recuperator also allows for the evaluation of a different manufacturing method and associated heat transfer assumptions. The Laser-SSHX uses a pattern of holes, distinct from the 3D-SSHX pattern. The laser cut sheets are thinner than the 3D-SSHX and so the stacking tolerances are expected to be different, directly impacting passage surface roughness. This in turn will impact recuperator heat transfer and pressure drop performance, differently, for each of the prototypes. This prototype is not as compact as the 3D-SSHX prototype, but at the commercial scale, it is significantly more cost-effective.

sCO_2 Heat Exchanger Test Facility

A sCO_2 test facility to evaluate sCO_2 compact heat exchanger (HX) performance was designed, assembled and operated with funding support from U.S. DOE NETL [5, 6]. The system was sized to reduce cost barriers associated with evaluating innovative ideas in HX design. [7]

The sCO_2 HX test loop, is a simple recuperated cycle, Figure 3, with a pump instead of a compressor and a pressure reducing valve used in place of the turbine. The reconfigurable test loop can accommodate test pressures up to 255 bar and temperatures up to 700°C. The sCO_2 mass flow rate can be adjusted up to 10 kg/min.

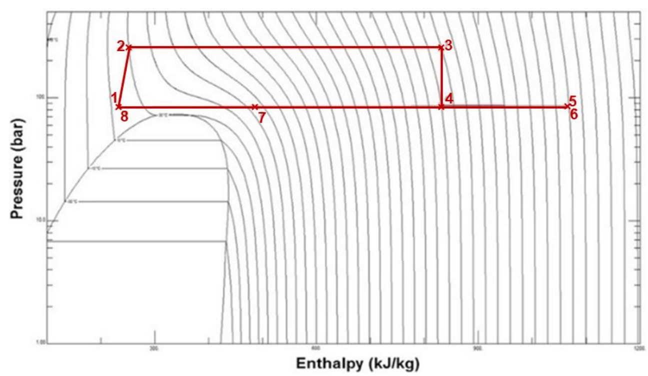


Figure 3. Simple recuperated cycle

Figure 4 shows the inside (a) and outside (b) portions of the test loop. The two SSHX prototype recuperators, 3D-SSHX and Laser-SSHX, Figure 4a, are mounted in the test loop so they can be tested independently, or in series.

Figure 5 is a simplified flow diagram for the HX test loop. A triplex piston pump, P1 with mass flow monitor (MFM), is used to pressurize and control sCO_2 flow. A surge tank is used to provide sCO_2 loop capacity and minimize flow variations associated with triplex pumps. This high-pressure, lower temperature stream, HP_{in}, enters the recuperator HX under test, picking up heat from the low-pressure, higher temperature stream, LP_{in}. The high-pressure stream, HP_{out}, on existing the recuperator passes through a pressure control valve, reducing the pressure before the heater, rather than after it. This is done to prevent overheating the control valve that is limited by the temperature rating, with safety factor, of ~500°C.

The LP_{in} stream passes through the primary heater where it is heated and enters the prototype recuperator under test. The LP_{out} stream, on exiting the recuperator, is cooled with water, passes through baffle pressure vessel and returns to the pump to be re-pressurized. After startup the CO_2 pressure is maintained at supercritical conditions throughout the loop.

The thermal/hydraulic performance of each SSHX recuperator prototype was evaluated over the range of temperatures, pressures and flows as show in Figure 6.

a) Inside **b) Outside**

Figure 4. sCO_2 heat exchanger test loop.

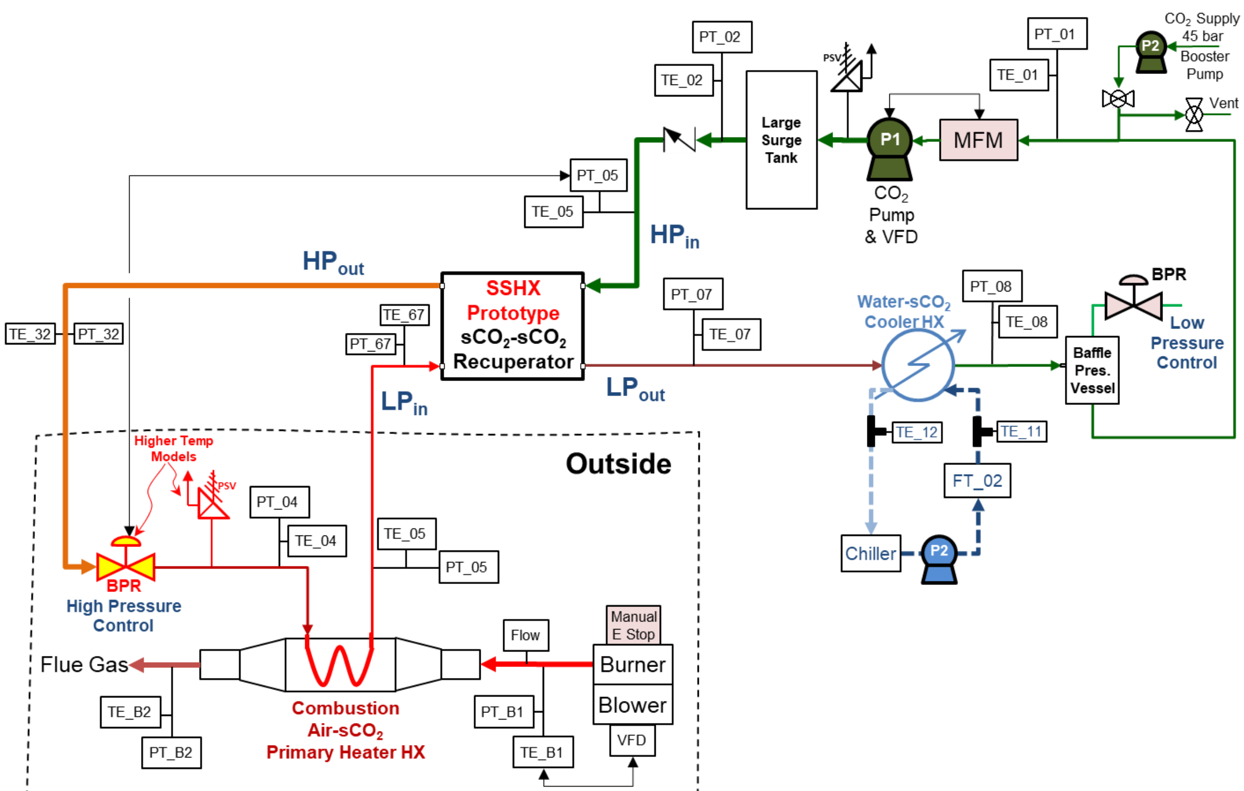


Figure 5. SSHX prototype recuperator simplified test loop flow diagram

RESULTS AND DISCUSSION

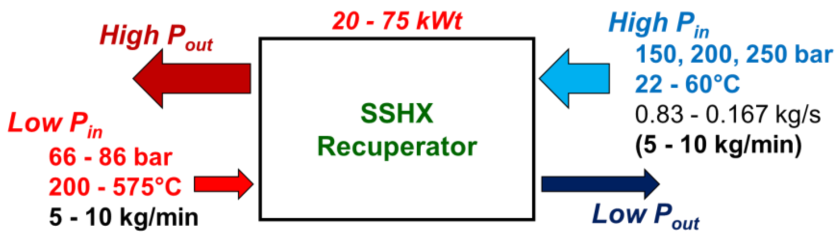


Figure 6. Thermal/hydraulic performance test conditions

HX performance tests were conducted by nominally changing the burner/blower exhaust air temperature from 200°C up to 700°C, in 50°C steps, each held for ~30 minutes. The test loop responded quickly to changes in flow, pressure, or temperature. At sCO_2 flow rates on the order of 7 kg/min, the system stabilized within 5-10 minutes for a step change of 50°C. Data is logged at 1 second intervals.

Figure 7 shows a typical recuperator performance test that when the hot combustion gas temperature is raised, the temperature of the low-pressure sCO_2 (80 bar), LP_{in}, entering the recuperator increases. Also observed is the temperature of the high-pressure sCO_2 (257 bar), HP_{out}, exiting the recuperator increases.

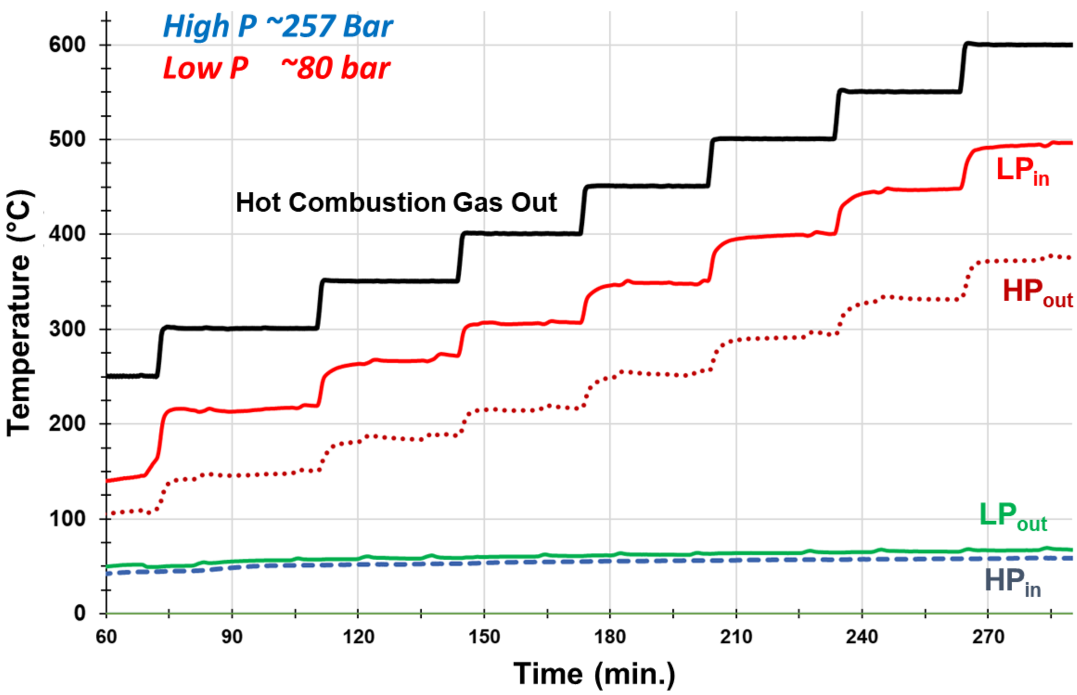


Figure 7. 3D-SSHX recuperator performance test plot.

For this HX performance test, the approach temperature is less than 10°C and is calculated by temperature difference between the low-pressure out stream, $LP_{out,}$ and the high-pressure in stream, HP_{in}.

Figure 8 presents an example summarizing the energy or heat balance for the 3D-SSHX prototype recuperator for the performance test shown in Figure 7. RefProp was used to calculate the enthalpy of the high-pressure and low-pressure sCO_2 streams (LP_{in}, LP_{out}, HP_{in}, HP_{out}), using their respective temperature and pressure measurements. For each data set, an energy balance is performed, to confirm system performance and data quality. For the SSHX prototype data sets examined, the energy balance error was less than 2%, indicating quality data sets.

Performance tests were conducted at three pressure range, 150 bar, 200 bar, and 250 bar, for each of the prototype recuperators. For each steady state test condition, the temperature, pressure and mass flow data are averaged for each of the fluid streams (LP_{in}, LP_{out}, HP_{in}, HP_{out}). These data were then used to calculate heat transfer, effectiveness, heat transfer coefficient, approach temperature and percent pressure drop per Shah/Sekulic [8].

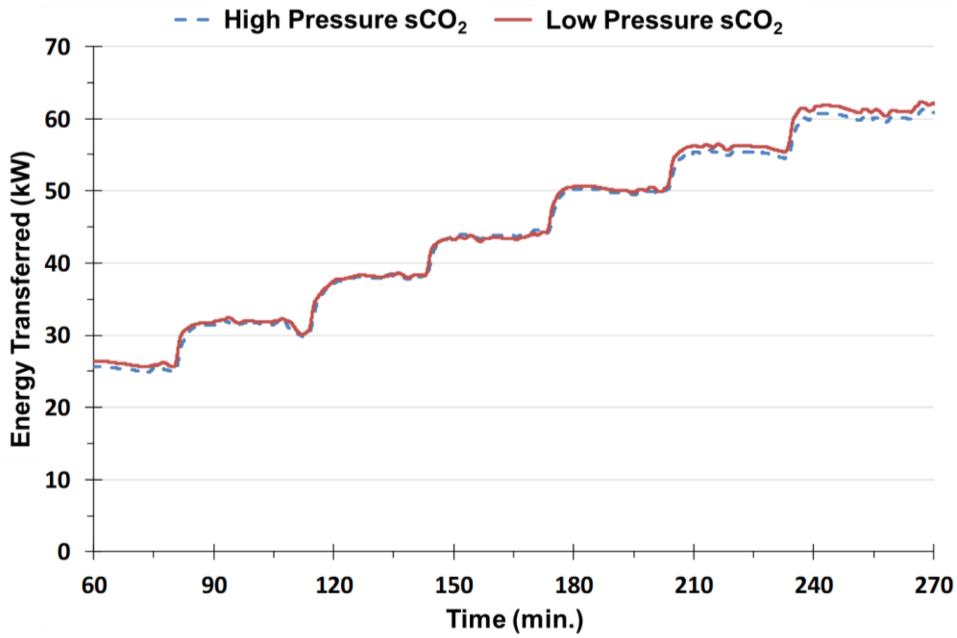


Figure 8. 3D-SSHX recuperator energy balance plot.

Figure 9 and Figure 10 are heat transfer plots for the 3D-SSHX and Laser-SSHX prototype recuperators. The x-axis is the recuperator lower pressure inlet temperature. The y-axis is the average heat transfer normalized by sCO_2 mass flow, $\dot{m}$. The plots summarize tests performed at 150 bar, 200 bar, and 250 bar and shows a linear response for each prototype.

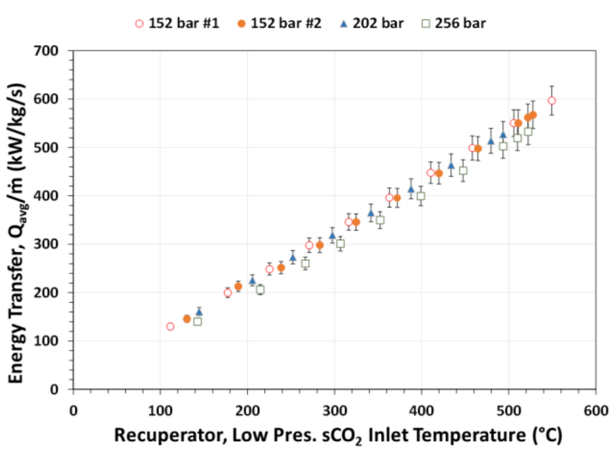


Figure 9. 3D-SSHX energy transfer plot.

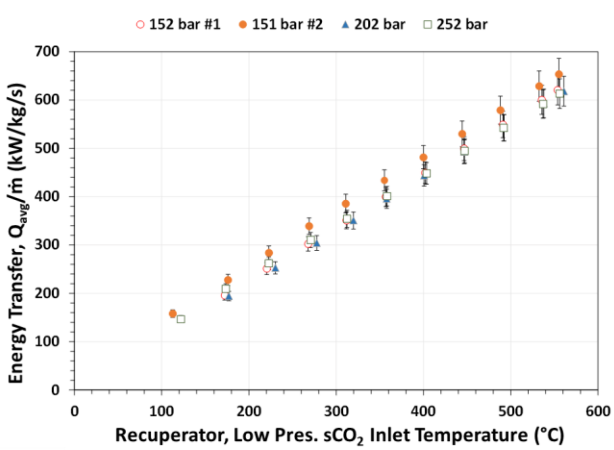


Figure 10. Laser-SSHX energy transfer plot.

Table 2 summarizes the thermal/hydraulic performance of each of the prototype SSHX recuperators at 500-550°C at 150, 200, and 250 bar. The 3D-SSHX recuperator met the program criteria with an average effectiveness of 96% and approach temperature of 9°C. The Laser-SSHX basically met the performance goals but had lower effectiveness and higher approach temperature than the 3D-SSHX. Measurement uncertainty could be improved by increasing the sampling time for each steady state condition and using more precise temperature and pressure measurements.

Table 2. Prototype SSHX Recuperator thermal/hydraulic performance at 500-550°C

Criteria	3D-SSHX	Laser-SSHX
Thermal Capacity (kWt)	77 ± 4%	82 ± 6%
Thermal Effectiveness (%)	96 ± 5%	93 ± 5%
Low Pressure ΔP_h (%)	1.5 ± 15%	1.2 ± 10%
High Pressure ΔP_c @ 250bar (%)	0.6 ± 23%	0.5 ± 17%
Approach Temperature (°C)	8.7 ± 12%	11.4 ± 21%
UA @ 250bar (W/°C)	1397 ± 5%	1125 ± 6%

The next two figures compare actual versus modeled 3D-SSHX recuperator performance using the data sets at ~150 bar, ~200 bar, and ~250 bar.

To characterize the prototype SSHX recuperators, thermal models based on code written in C++, employed discretized calculations. This was done in part to compensate for large sCO_2 property changes that can occur with small variations in temperature and pressure. For the sCO_2 micro-passages, the Petukhov [9] equation was selected to calculate the Nusselt number and the Bhatti and Shah's model [10] was selected to calculate pressure drop.

Figure 11 compares the actual energy transfer with the model predictions. Figure 12 compares the actual effectiveness, ϵ, with the model predictions. In both examples, there is good correlation, within the error bars of ± 5%, between model or predicted recuperator performance and the actual or measured performance data.

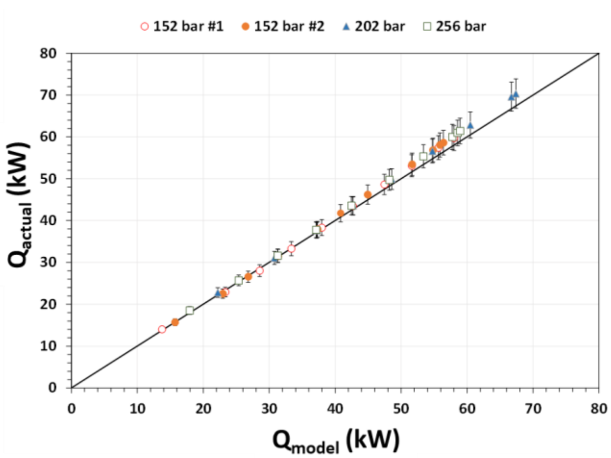


Figure 11. 3D-SSHX actual vs modeled energy transfer plot.

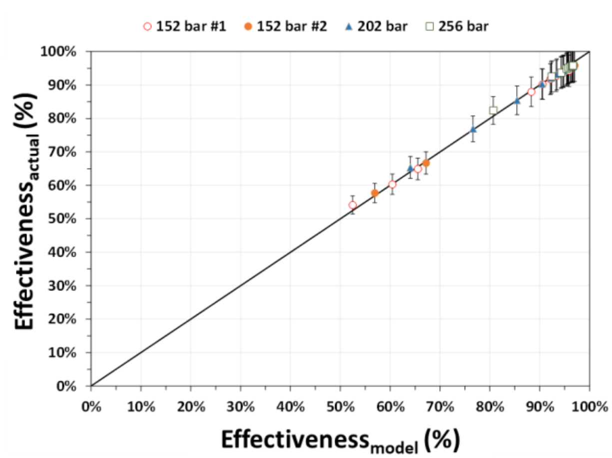


Figure 12. 3D-SSHX actual vs. modeled effectiveness plot.

MWt Scale Recuperator

As part of the project, the Laser-SSHX recuperator concept was scaled to 46 MWt thermal capacity with the thermal/hydraulic criteria in Table 1. The analysis showed that factory assembling a recuperator made up of a number of sub-modules was more cost effective. Sub-module fabrication allows for tighter manufacturing tolerances which are more in line with the manufacturing sweet spot. This allows for more compact designs using less metal, and for economies of scale cost reductions.

Sub-module size design tradeoffs were evaluated. Fewer sub-modules lower the number of header connections and their associated costs. Larger sub-module sizes are more difficult to manufacturer and maintain uniform flow distribution without increasing their associated pressure drop. CFD modeling was used refine manifold design and sub-module size.

There are a number of options in how sub-modules can be factory assembled to yield a 46 MWt Laser-SSHX recuperator. The example shown in Figure 13 is of a 46MWt recuperator divided into eight parallel sub-modules, with overall dimensions of 0.5m x 2.8m x 3m. Cost analysis of the SSHX recuperator concept shows the potential for the n^{th} of a kind production cost on the order of a third of the programs' criteria. To show the promise of 3D printing to produce the SSHX recuperator, calculations were performed based on the prototype 3D-SSHX. Compared to the Laser-SSHX at 46MWt, the size of the 3D printed recuperator size would reduce to 0.3m x 2.1m x 2.3m, a 57% decrease in volume.

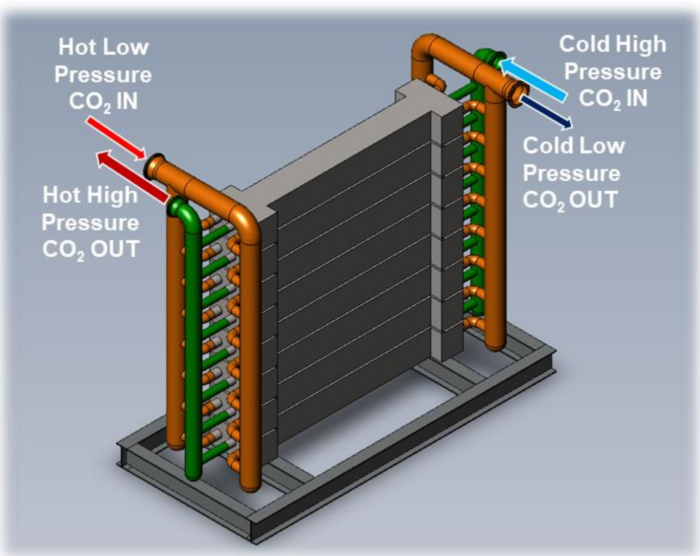


Figure 13. 46 MWt recuperator composed of eight parallel Laser-SSHX modules

CONCLUSIONS

An introduction into a new recuperator concept, SSHX, has been presented. Two prototypes were designed and fabricated using different fabrication methods and materials. The 3D-SSHX prototype recuperator was made of Inconel 625 using 3D printing. The Laser-SSHX was made of stainless steel 347H using laser cut sheets.

The two prototypes were mounted in the HX test facility where thermal/hydraulic performance testing at Brayton power cycle conditions was conducted.

Analyzed test data indicated that the SSHX prototype recuperators met or exceeded the performance design goals for effectiveness, approach temperature and pressure drop. Additionally, there was good correlation between design and actual recuperator performance data. An example of how the SSHX recuperator concept could be cost effectively scaled to the 46 MWt capacity using a factory assembled, modular approach was presented.

Future work includes refining the SSHX design models and developing a robust manufacturing process.

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