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TESTING OF COMPACT RECUPERATORS FOR A SUPERCRITICAL CO_2 BRAYTON POWER CYCLE

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ABSTRACT

Practical implementation of a Supercritical CO_2 (S-CO_2) Brayton power cycle is dependent on successful development of a power dense and robust recuperator design compatible with the operating pressures and temperatures of the cycle.

This paper describes the testing of two compact heat transfer surfaces in the form of two recuperators. One surface employs a wire-mesh as the extended heat transfer surface, and the other surface employs a folded-wavy-fin as the extended heat transfer surface. The 200 kW recuperators for either surface use a brazed and welded unit-cell heat exchanger construction technique. In both cases, the assembly is formed in a way that allows independent header deflection enabled by internal slip planes within the heat transfer core region. The resulting assemblies are compact to the point that they can easily be accommodated within standard piping to provide overall pressure containment; however, the brazed assembly holds promise to withstand system pressure on its own.

Thermal-hydraulic testing showed that the compact recuperator employing the traditional, folded-wavy-fin heat transfer surface achieved the design heat transfer rate with less than half the allowable pressure drop. Similar testing of the compact recuperator employing the novel, wire-mesh heat transfer surface remains uncertain with the low mass flow rate due to the large flow resistance on the high pressure side. For the low pressure side, the measured pressure drop was roughly consistent with the expected pressure drop for the mass flow rate. Therefore, the wire-mesh heat transfer surface remains viable suggesting additional development is warranted.

INTRODUCTION

Practical implementation of a Supercritical CO_2 (S-CO_2) Brayton power cycle is dependent on successful development of a power dense and robust recuperator design compatible with the operating pressures and temperatures of the cycle. Overall compactness of the recuperator design significantly impacts arrangement flexibility and cost, while mechanical compliance provides tolerance to the intrinsic increase in thermo-mechanical loading of compact heat exchangers. The high power density and thermal stress tolerant design will have a direct bearing on unit design life and the performance of the system.

This paper describes the testing of two compact heat transfer surfaces in the form of two recuperators. One surface employs a wire-mesh as the extended heat transfer surface, and the other surface employs a folded-wavy-fin as the extended heat transfer surface. The 200 kW recuperators use a brazed and welded unit-cell construction technique. The wire-mesh heat exchanger is expected to have a heat transfer area per unit volume of 7,000-8,000 m^2/m^3, and the folded-wavy-fin heat exchanger is expected to have a heat transfer area per unit volume of 3,300-4,500 m^2/m^3. In both cases, the assembly is formed in a way that allows independent header deflection enabled by internal slip planes within the heat transfer core region. The resulting assemblies are compact to the point that they can easily be accommodated within standard piping to provide overall pressure containment; however, the brazed assembly holds promise to withstand system pressure on its own.

BACKGROUND

Bechtel Marine Propulsion Corporation (BMPC) is developing compact heat exchanger technology in support of the development of a closed, recuperated Brayton cycle using S-CO_2 as the working fluid [1]. This development began with testing a shell-and-tube heat exchanger designed and fabricated by Tex-Fin, Inc. using low-finned tubes for increasing the heat transfer surface area on the shell side [2,3]. The increase in the surface area reduced the overall size of the heat exchanger by one third as compared to a heat exchanger with smooth tubes. The heat exchanger successfully transferred heat from S-CO_2 on the shell side to water on the tube side at the design rate of 100 kW at the specified inlet conditions.

In parallel, BMPC and Brayton Energy LLC have been working to adapt the recuperator technology used by Brayton Energy LLC for a higher pressure, S-CO_2-to-S-CO_2 recuperator. With the thermal-physical characteristics of the S-

CO_2, Brayton Energy LLC proposed a novel wire-mesh heat transfer surface as a potential improvement over an established folded-wavy-fin surface to further intensify the heat transfer rate. The wire-mesh heat exchanger is expected to achieve an even higher degree of power density and to provide the required fatigue endurance at a competitive cost.

HEAT EXCHANGER DESCRIPTION

Brayton Energy, LLC designed and fabricated two small-scale heat exchangers to demonstrate the heat exchanger technology for transferring heat to and from S-CO_2. Both heat exchangers are designed to provide a heat transfer rate of 200 kW for the conditions listed in Table 1.

Table 1: Inlet Conditions for the Small-Scale Heat Exchanger Testing

Inlet Conditions	High Pressure Side	Low Pressure Side
Fluid	CO_2	CO_2
Mass Flow Rate	2.5 lbm/sec	2.5 lbm/sec
Fluid Temperature	150°F	400°F
Fluid Pressure†	1,410 psia	1,400 psia

† The bases for theses pressure values are described later

Figure 1 shows a sketch of the folded-wavy-fin heat transfer surface, and Figure 2 shows a rendering of the wire-mesh heat transfer surface along with the local flow configuration. The two low pressure paths (blue arrows) are brazed to the high pressure path (red arrow).

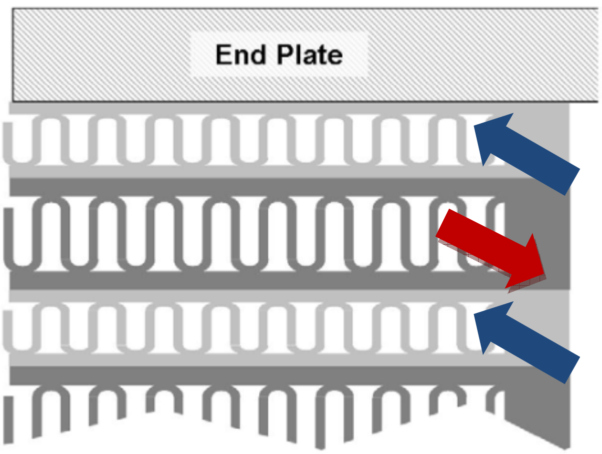

Figure 1 Sketch of the wavy-fin heat transfer surface and the associated flows

The heat exchanger with the wire-mesh as the heat transfer surface achieved a ratio of the heat transfer area to unit volume of 7,000-8,000 m^2/m^3 compared to 4,000-5,000 m^2/m^3 for a similar heat exchanger with folded-wavy-fins as the heat transfer surface.

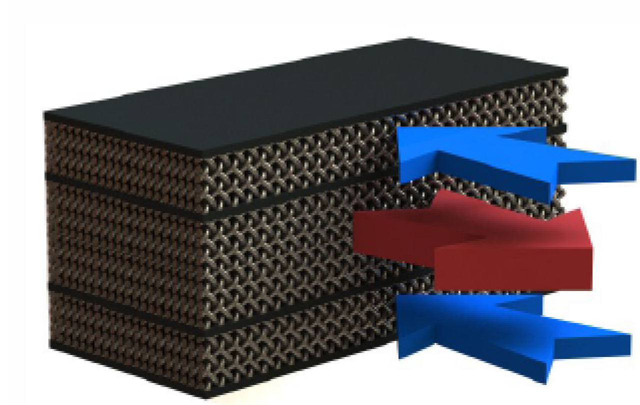

Figure 2 Rendering of a detail of the wire-mesh heat transfer surface and the associated flows

The prototype heat exchangers were prepared for testing by furnace brazing unit-cells and welding these cells together to create the heat exchanger cores. This approach began with the fabrication of subassemblies referred to as unit-cells. These unit-cells consisted of either wire-mesh or folded-wavy-fins extended surfaces that were brazed to parting sheets forming the fluid pass regions and the pressure boundaries and thus providing the compact heat transfer surfaces. The fabrication process individually assembled, brazed and leak tested each unit-cell. Individual cells were leak tested to a bubble-tight standard, and the heat exchanger assembly was tested to a 0.1 percent maximum leak rate standard. Leak testing each unit-cell provided a means of quality control of the construction prior to full heat exchanger assembly.

Figure 3 shows a photograph of unit-cells for each heat transfer surface. The figure also shows the predicted length reduction allowed by the wire-mesh surface as compared to the folded-wavy-fin surface for the same capacity.

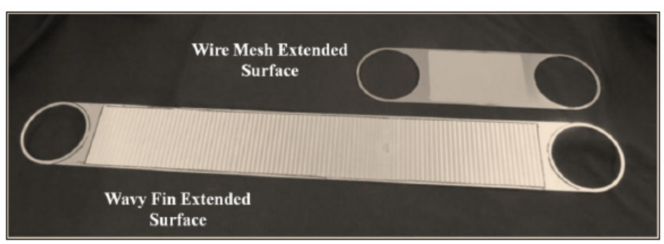

Figure 3 Photograph of wire-mesh unit-cell side-by-side with a folded-wavy-fin unit-cell

The fabrication process completed the heat exchangers by stacking the unit-cells and welding the unit-cells together in the header region only. As a result the heat exchanger retained the ability for cell-to-cell flexure, allowing the two headers to expand/contract independently. This compliance is expected to provide exceptional fatigue endurance. Figure 4 shows renderings of each small-scale heat exchanger.

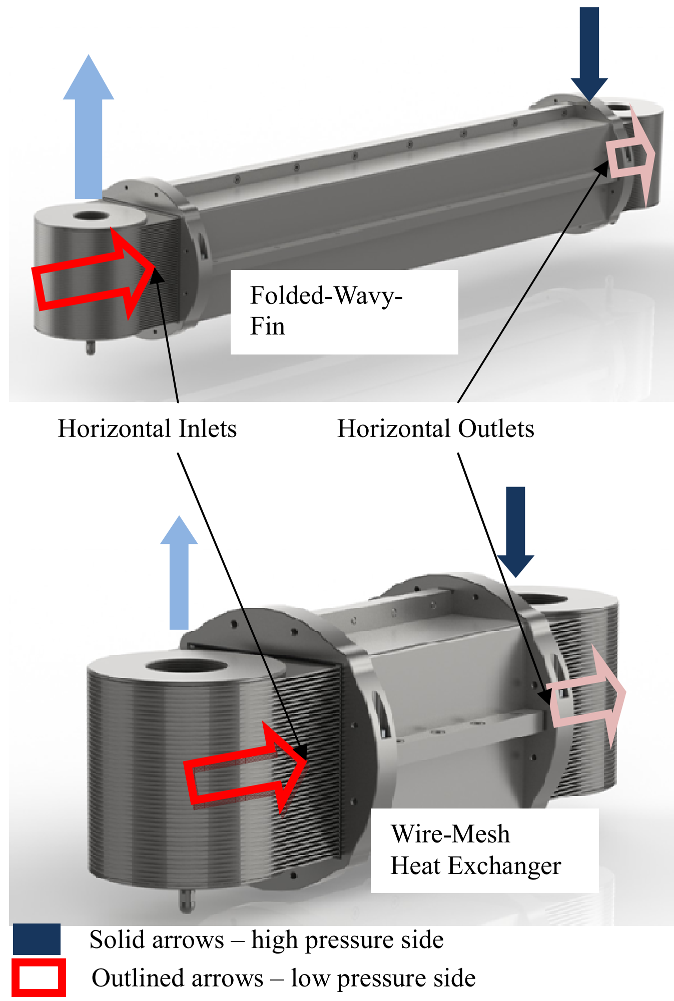

Figure 4 Renderings of the small-scale heat exchangers with arrows showing the flow configuration

HEAT EXCHANGER TESTING

The objective of the testing was to verify the thermal-hydraulic performance of the heat transfer surfaces configured as representative heat exchangers.

In an effort to keep testing costs manageable, the test conditions were chosen within the capacities of available equipment. As a result CO_2 in the loop was circulated with a pump in place of a compressor. Therefore the "high pressure" flow stream (which represents the compressor discharge) was ~1,000 psig lower then the pressure expected for a closed Brayton power cycle (see Table 1). On the other hand, the "low pressure" flow stream, which represents the turbine discharge condition, operated at its actual condition. The simplified test configuration significantly reduced the cost of the test loop, yet provided the necessary instrumentation to verify the performance of the wire-mesh and folded-wavy-fin heat transfer surfaces in representative heat exchanger configurations.

The prototype heat exchangers were installed in a pipe used as a pressure vessel and constructed to mount the heat exchanger cores, minimize bypass-leakage on the low-pressure side, and provide flange connections to the test loop, as shown in Figure 5. The heat exchangers were slid into the pipe, and the high-pressure sides were aligned with the inlet and outlet manifold connections. This configuration simplified the manifolds and the pressure boundary for the testing and represents a possible arrangement for an actual energy conversion system.

For the low pressure side of the heat exchanger, the S-CO_2 flowed from the smaller diameter loop piping into the larger diameter pipe containing the heat exchanger. The S-CO_2 then entered the horizontal inlets on a vertical surface on either side of the heat exchanger and exited the horizontal outlets on a vertical surface on either side of the heat exchanger as indicated in Figure 4.

For the high pressure side of the heat exchanger, the S-CO_2 flowed through the vertical manifold connections into and out of the heat exchanger as shown in Figure 4 and Figure 5. The larger diameter pipe section contains two sets of vertical manifolds. For testing the folded-wavy-fin heat exchanger, the set of vertical manifolds with the larger spacing was used as the inlet and the outlet of the S-CO_2. The other set of vertical manifolds was used for instrumentation. For testing the wire-mesh heat exchanger, the set of vertical manifolds with the smaller spacing was used as the inlet and the outlet of the S-CO_2. The other set of vertical manifolds was used for instrumentation.

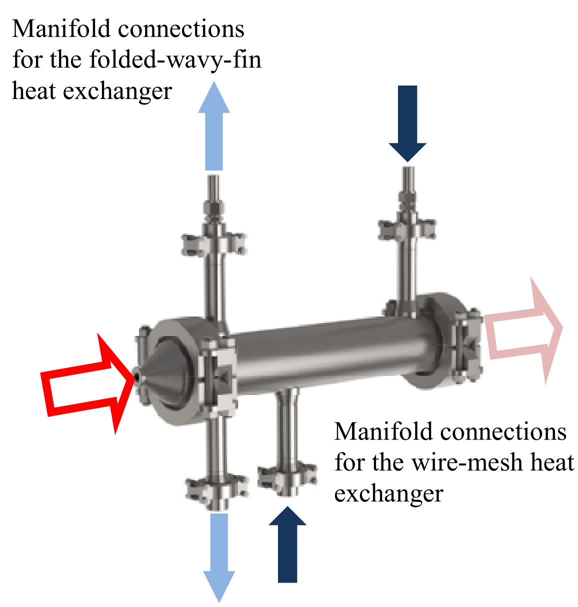

Figure 5 Rendering of the test section for the small-scale heat exchangers (see legend in Figure 3)

Figure 6 shows an overview of the test loop used in the testing of the prototype heat exchangers. Both the chiller and the heater are heat exchangers with water on one side and CO_2 on the other side. The chiller uses river water to cool the CO_2, and the heater uses water heated using electrical resistance to heat the CO_2. The pump is a magnetic coupled, centrifugal pump.

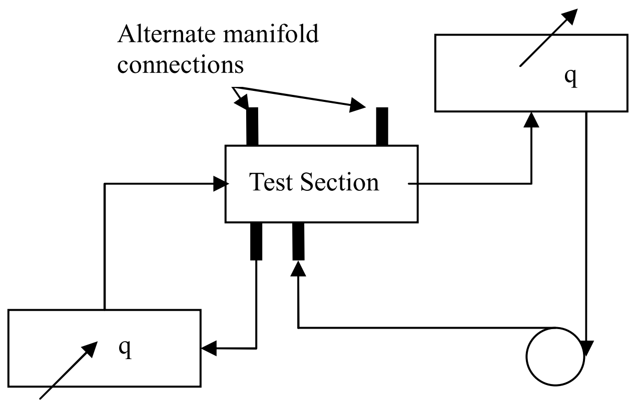

Figure 6 Test loop configuration

RESULTS

The thermal-hydraulic testing of the compact recuperator employing the traditional, folded-wavy-fin heat transfer surface achieved the design heat transfer rate with less than half the allowable pressure drop. Similar testing of the compact recuperator employing the novel, wire-mesh heat transfer surface showed a limited flow rate due to a large flow resistance on the high pressure side of the recuperator.

Testing of the recuperator using the traditional, folded-wavy-fin heat transfer surface varied the inlet temperatures, inlet pressures, and the mass flow rates to explore the thermal-hydraulic performance of the heat exchanger. To present the thermal performances of the recuperator for these data, the measured thermal performance is shown as a function of the maximum heat transfer rate calculated using the measured inlet conditions in Figure 7. The error bars in the figure represent the expanded uncertainty of the heat transfer rate (±8.22 kW).

The average effectiveness of the measured thermal performance of the recuperator using the traditional, folded-wavy-fin heat transfer surface was 0.80, as indicated in Figure 7. The design effectiveness of the recuperator was 0.90, also shown on the figure.

The measured hydraulic performance of the recuperator using the traditional, folded-wavy-fin heat transfer surface is shown in Figure 8 and Figure 9. In these figures the measured pressure drop across each side of the heat exchanger is shown as function of the mass flow rate. The expanded uncertainty for the pressure drop measurement is 2.89E-03 psid – too small to appear on the figures.

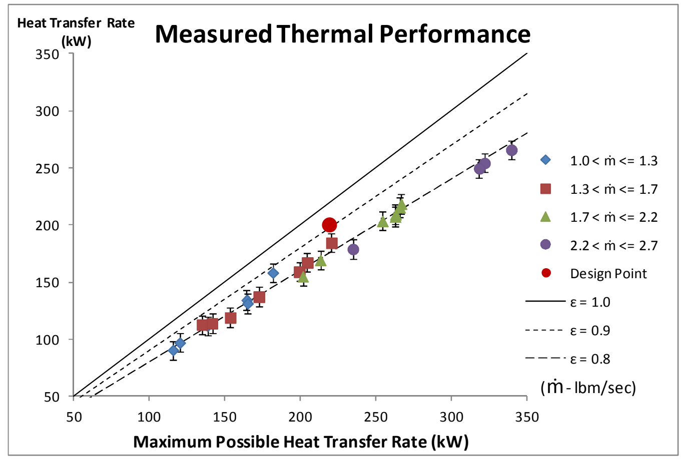

Figure 7 Measured thermal performance showing the effectiveness of the recuperator using the traditional, folded-wavy-fin heat transfer surface

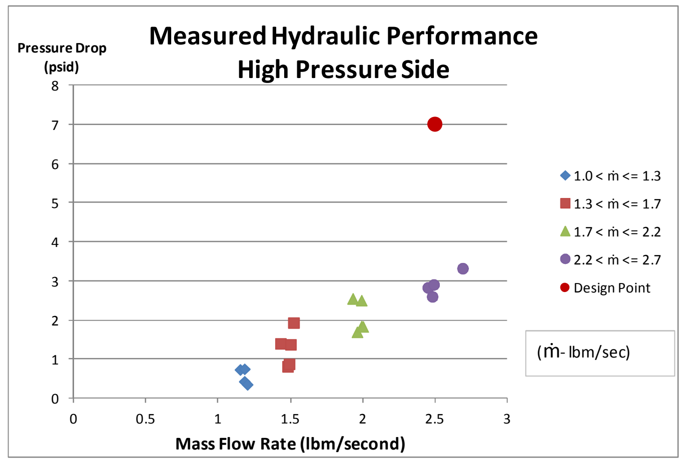

Figure 8 Measured hydraulic performance for the high pressure side of the recuperator using the traditional, folded-wavy-fin heat transfer surface

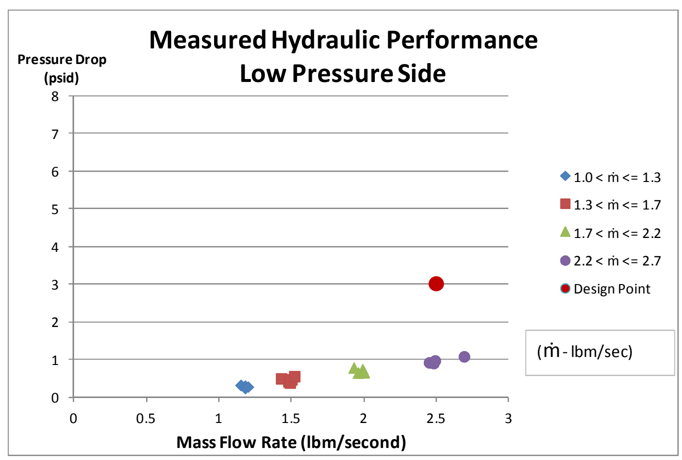

Figure 9 Measured hydraulic performance for the low pressure side of the recuperator using the traditional, folded-wavy-fin heat transfer surface

Testing of the recuperator using the novel, wire-mesh heat transfer surface was limited due to the large flow resistance on the high pressure side of the recuperator. With the limited flow, however, the pressure drop on the low pressure side was roughly consistent with the expected pressure drop.

DISCUSSION

The compact recuperator employing the traditional, folded-wavy-fin heat transfer surface performed well in the thermal-hydraulic testing confirming the established fabrication and design knowledge for heat exchangers using this heat transfer surface. With the measured pressure drop less than half the allowable, additional design margin exists. The folded-wavy-fin heat transfer surface can provide the thermal-hydraulic performance necessary for a recuperator in a closed, Brayton cycle using S-CO_2.

The thermal-hydraulic performance of the compact recuperator employing the novel, wire-mesh heat transfer surface remains uncertain with the low mass flow rate due to the large flow resistance on the high pressure side. The cause of the large flow resistance on the high pressure side is unknown for now. The fabrication of the first prototype recuperator taught the following:

- The wire-mesh material is difficult to cut cleanly without plastically deforming the cut surfaces
- The compaction factor of the wire-mesh material is currently uncontrolled increasing the performance uncertainty

Both compact recuperator designs employed the configuration that allows the ability for cell-to-cell flexure providing compliance and thus fatigue endurance of the overall heat exchanger. Although only thermal-hydraulic results have been presented in this paper, the recuperator configuration was chosen based on successful designs of other recuperators to provide fatigue endurance as well as a high specific heat transfer rate.

For either heat transfer surface, the brazed and welded unit-cell heat exchanger construction may provide the pressure boundary for system pressure with further development. Of course, the compactness of the heat exchangers allows the testing to occur within a pressure vessel fabricated from standard piping to contain the system pressure, as was done with the tested recuperators described in this paper.

CONCLUSIONS

Thermal-hydraulic testing showed that the compact recuperator employing the traditional, folded-wavy-fin heat transfer surface achieved the design heat transfer rate with less than half the allowable pressure drop. Testing showed that the folded-wavy-fin heat transfer surface provides a compact recuperator for energy conversion using S-CO_2 as the working fluid.

Similar testing of the compact recuperator employing the novel, wire-mesh heat transfer surface remains uncertain with the low mass flow rate due to the large flow resistance on the high pressure side. For the low pressure side, the measured pressure drop was roughly consistent with the expected pressure drop for the mass flow rate. Therefore, the wire-mesh heat transfer surface remains viable suggesting additional development is warranted.

FUTURE ACTION

Working together, BMPC and Brayton Energy LLC will determine the cause of the large pressure drop on the high pressure side of the wire-mesh recuperator, adjust the material requirement and fabrication procedures as required, and continue to develop compact heat transfer surfaces and heat exchangers for a closed, Brayton cycle for energy conversion using S-CO_2 as the working fluid.

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