# Thermal-Hydraulic Testing of a Compact, Diffusion Bonded Heat Exchanger for a Supercritical $CO_2$ Brayton Power Cycle

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## ABSTRACT

Heat exchangers are an enabling technology for efficient power generation with a closed, recuperated Brayton cycle using supercritical $CO_2$ as the working fluid. The heat exchangers impact the overall system efficiency (operating cost) and size (installation cost). The heat exchanger designs must balance between heat exchanger effectiveness and pressure drop to achieve the desired tradeoff between system efficiency and system size. This tradeoff between system efficiency and system size will vary for a given application of the energy conversion system.

Naval Nuclear Laboratory (NNL) completed the initial thermal-hydraulic testing of a compact heat transfer surface in the form of a water-to-$CO_2$ heat exchanger designed and fabricated by CompRex LLC. The heat transfer surface results from the diffusion bonding of a stack of chemically etched thin plates (≈0.6mm). Square and rectangular perforations within the plates are offset relative to adjacent plates to form flow paths. Dividing plates and the exterior pressure boundary result from stacking plates without etched perforations or without etched perforation in local regions. Post bonding, headers and manifolds are welded to the resulting block to complete the heat exchanger.

The thermal-hydraulic testing showed that the compact water-to-$CO_2$ heat exchanger performed well. The heat exchanger achieved a greater than 90 percent effectiveness, and the pressure drop values matched the predicted pressure drop values on the $CO_2$ side of the heat exchanger. Although the pressure drop across the water side was greater than expected for this first prototype, the design can be easily adjusted in future units.

## INTRODUCTION

Heat exchangers are an enabling technology for efficient power generation with a closed, recuperated Brayton cycle using supercritical $CO_2$ ($sCO_2$) as the working fluid. The heat exchangers impact the overall system efficiency (operating cost) and size (installation cost). The heat exchanger designs must balance between heat exchanger effectiveness and pressure drop to achieve the desired tradeoff between system efficiency and system size. This tradeoff between system efficiency and system size will vary for a given application of the energy conversion system.

Naval Nuclear Laboratory (NNL) has developed compact heat exchanger technology in support of the development of a $sCO_2$ Brayton power cycle [1-3]. This development has evaluated and tested several heat transfer surfaces, including low-finned tubes, folded wavy-fin, and wire-mesh [4-8].

This paper describes the initial thermal-hydraulic testing of a compact heat transfer surface in the form of a water-to-$CO_2$ heat exchanger designed and fabricated by CompRex LLC. The heat transfer surface results from the diffusion bonding of a stack of chemically etched thin plates (≈0.6mm). Square and rectangular perforations within the plates are offset relative to adjacent plates to form flow paths. Dividing plates and the exterior pressure boundary result from stacking plates without etched perforations or without etched perforation in local regions. Post bonding, headers and manifolds are welded to the resulting block to complete the heat exchanger.

## RESULTS AND DISCUSSION

Thermal-hydraulic testing showed that the compact heat transfer surface in the form of a water-to-$CO_2$ heat exchanger performed well at the inlet conditions achieved during the testing. With the inlet temperature on the water side lower than the acceptance inlet value and the inlet temperature on the $CO_2$ side higher than the acceptance inlet value, the measured heat transfer rate was less than the expected value at the acceptance inlet conditions. At the measured conditions, the effectiveness of the heat exchanger ranged between 94-99 percent.

Moreover, the measured pressure drop across the $CO_2$ side at the acceptance inlet mass flow rate was lower than the predicted pressure drop. The measured pressure drop across the water side, however, was higher than expected. The initial testing did not achieve the mass flow rate at the acceptance inlet condition, but the pressure drop at lower flow rates is already about equal to expected pressure drop at the acceptance inlet condition. Additional testing is planned to determine the reason for the difference.

Figure 1 shows the calculated thermal performance based on measured values of the water-to-$sCO_2$ heat exchanger. This figure shows the calculated average heat transfer rate as a function of the maximum heat transfer rate. As shown later, both of these calculated values use the measured inlet and outlet temperatures and pressures as well as the measured mass flow rates. The figure also distinguishes between two groups of mass flow rates. The figure shows the acceptance inlet point and indicates two values of heat exchanger effectiveness to indicate the measured performance of the heat exchanger. Finally, the expanded uncertainty of the heat transfer rate at the acceptance inlet conditions is ±1.981 kW for the $CO_2$ side and ±9.45 kW for the water side.

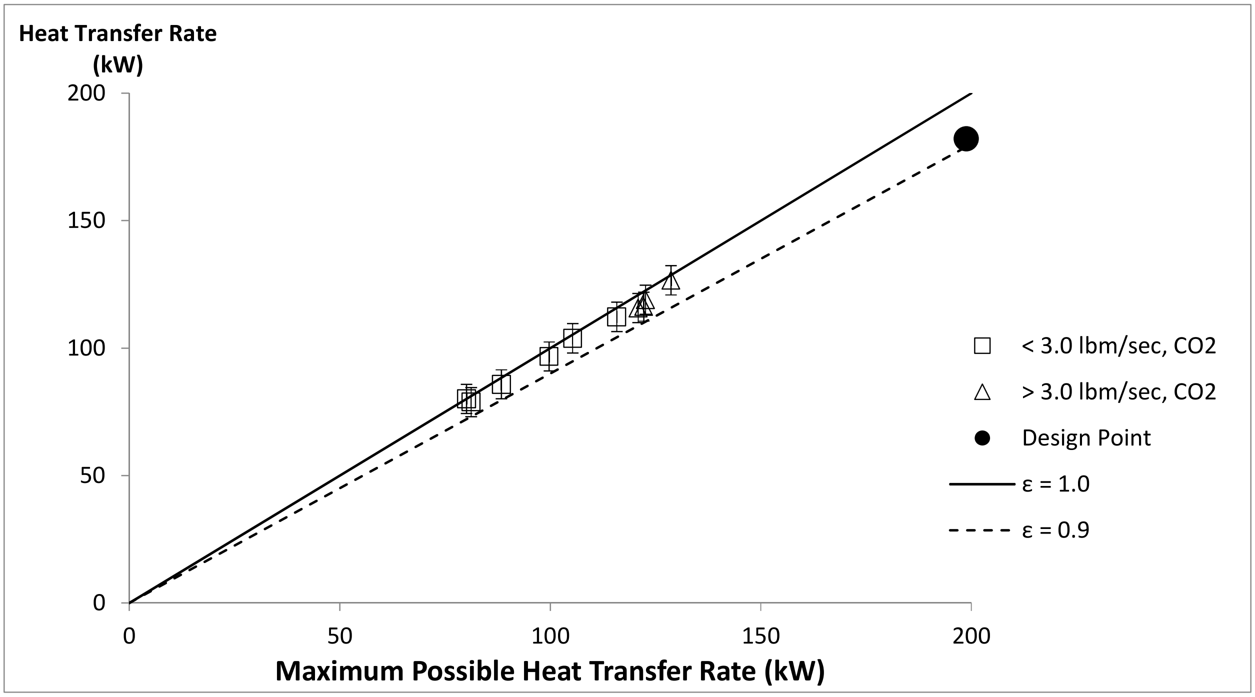


Figure 1. Measured thermal performance showing the effectiveness of the water-to-s$CO_2$ heat exchanger (expanded uncertainty of the heat transfer rate shown is ±5.72 kW - the average of the uncertainties for the $CO_2$ side and the water side)

For the associated hydraulic resistance, Figure 2 shows the visual presentation of the measured data. Finally, the expanded uncertainty for the pressure drop measurement is 0.003 psid as determined by a measurement uncertainty assessment. With the small magnitude of the expanded uncertainty, the figures contain no error bars.

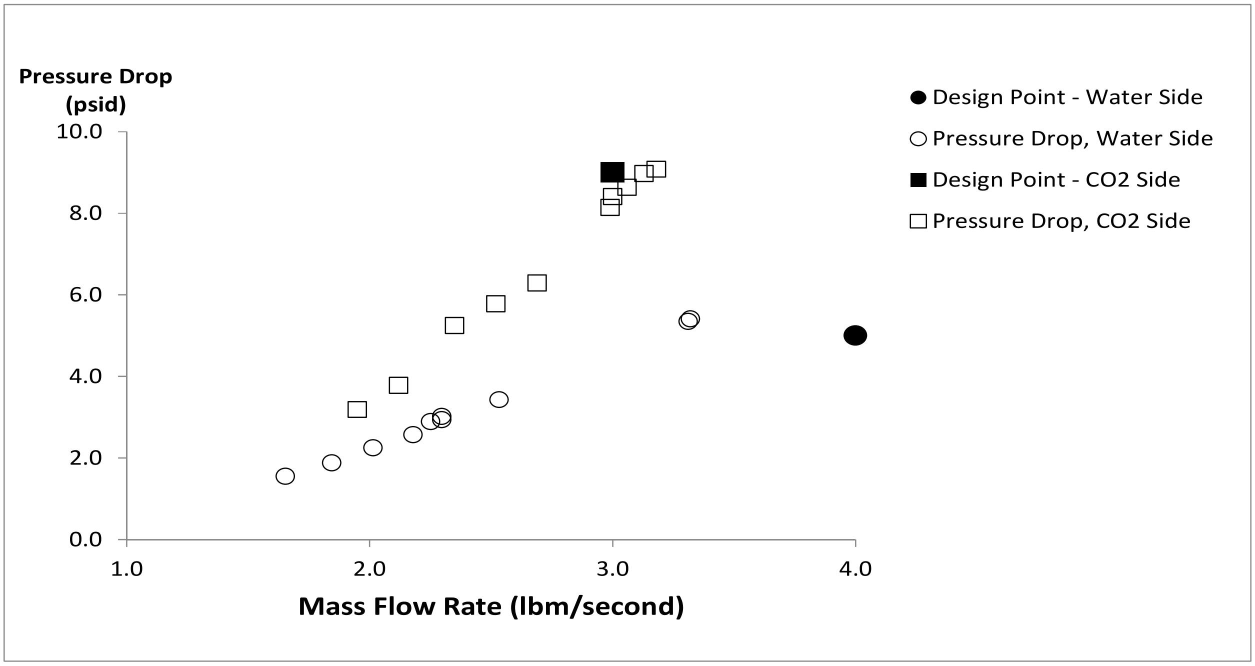


Figure 2. Measured hydraulic resistance of the heat exchanger (expanded uncertainty of the pressure drop is ±0.003 psid)

The testing results suggest a few observations, including the projected heat transfer rate at the reference or acceptance inlet conditions.

As shown in Figure 1, the heat exchanger testing measured the performance of the heat exchanger at operating conditions approaching the acceptance inlet conditions but not at these conditions. The projected heat transfer rate of the heat exchanger at the acceptance inlet conditions based on the measured performance is 193 $kW_{th}$. The basis of this projected value follows:

$$q = (\varepsilon)(q_{maximum})$$

With,

$q$ – Heat transfer rate, kW

$\varepsilon$ – Effectiveness of the heat exchanger, dimensionless

$q_{maximum}$ – Maximum heat transfer rate (ideal heat transfer rate), kW

The heat transfer rate and the maximum heat transfer rate shown in Figure 1 are based on the measured values of inlet and outlet pressures and temperatures as well as the measured values of the mass flow rate. The projected heat transfer rate at the acceptance inlet conditions based on the average of the effectiveness values for the measured conditions is 193 $kW_{th}$. The maximum heat transfer rate for the acceptance inlet condition is known based on the prescribed inlet temperatures and pressures as well as the mass flow rate.

Averaging the effectiveness values based on the measured conditions assumes that the thermal conductance at the acceptance inlet conditions is represented by the thermal conductance at the measured conditions. As the following shows, the effectiveness is a function of the number of transfer units and the heat capacity ratio:

$$\varepsilon = \frac{1 - e^{\left(-NTU(1-C_r)\right)}}{1 - C_r e^{\left(-NTU(1-C_r)\right)}}$$

With,

$NTU$ – Number of transfer units, dimensionless

$C_r$ – Heat capacity ratio $C_r = {C_{minimum}}/{C_{maximum}}$, dimensionless

And,

$$NTU = \frac{UA}{C_{minimum}}$$

$UA$ – Thermal conductance (product of the overall heat transfer rate, U, and the heat transfer surface area, A), kW / K

$C_{minimum}$ – Minimum heat capacity rate between the fluids within the heat exchanger, kW / K

As shown, the number of transfer units is a function of the thermal conductance and the minimum heat capacity rate. The value of the heat transfer area is constant and known. The minimum heat capacity rate at the acceptance inlet condition is also known. The value of the overall heat transfer coefficient is unknown at the acceptance inlet condition. Averaging the effectiveness values based on the measured conditions represents an average of the measured values of the overall heat transfer coefficient. The projected heat transfer rate at the acceptance inlet conditions therefore assumes that the overall heat transfer coefficient at the acceptance inlet conditions is represented by the average of the overall heat transfer coefficients at the measured conditions.

The projected heat transfer rate is five to seven percent greater than the 180-185 $kW_{th}$ heat transfer rate predicted by CompRex.

The results indicate that pressure drop on the $CO_2$ side meets the specification; whereas, the water side pressure drop does not. NNL and CompRex are exploring the cause of the higher than expected pressure drop. The water within the test loop was found to contain particles that may have lodged in the water side flow passages.

After initial loop operations, a filter installed upstream of the water inlet did collect particles from the water. This collection of particles in the filter may explain the reduced water flow achieved during the testing but would not explain the higher differential pressure across the water side of the heat exchanger since the filter was upstream of the measurement. During a subsequent shutdown of the loop, the heat exchanger was back flushed; but no appreciable amount of debris was found in the water flushing the water side of the heat exchanger.

## CONCLUSIONS

The compact heat transfer surface in the form of a water-to-$CO_2$ heat exchanger performed well in the thermal-hydraulic testing. The testing of the first-of-a-kind heat exchanger confirms the fabrication and design knowledge for the heat transfer surface consisting of a diffusion bonded stack of chemically etched thin plates (≈0.6mm).

## REFERENCES

1. Clementoni, E.M., et al., *Test Facilities*, in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO$_2$) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Editors. 2017.
2. Clementoni, E.M., T.L. Cox, and M.A. King, *Transient Power Operation of a Supercritical Carbon Dioxide Brayton Cycle*, in *ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*. 2017, ASME: Charlotte, North Carolina, USA.
3. Ashcroft, J., K. Kimball, and M. Corcoran, *Overview of Naval Reactors Program Development of the Supercritical Carbon Dioxide Brayton System*, in *Supercritical $CO_2$ Power Cycle Symposium*. 2009: Troy, New York, USA.
4. Fourspring, P.M. and J.P. Nehrbauer. *Heat Exchanger Testing For Closed, Brayton Cycles Using Supercritical $CO_2$ as The Working Fluid*. in *2011 Supercritical $CO_2$ Power Cycle Symposium*. 2011. Boulder, Colorado, USA.
5. Fourspring, P.M. and J.P. Nehrbauer. *The Variation in Effectiveness of Low-Finned Tubes within a Shell-and-Tube Heat Exchanger for Supercritical $CO_2$ (ICONE20POWER 2012-54116)*. in *Proceedings of the 20th International Conference on Nuclear Engineering (ICONE20), Proceedings of the ASME 2012 Power Conference (POWER2012)*. 2012. Anaheim, California, USA.
6. Fourspring, P.M., et al. *Testing of Compact Recuperators for a Supercritical $CO_2$ Brayton Power Cycle*. in *4th International Symposium on Supercritical $CO_2$ Power Cycles*. 2014. Pittsburgh, Pennsylvania, USA.
7. Fourspring, P.M. and J.P. Nehrbauer. *Performance Testing of the 100kW Shell-and-Tube Heat Exchanger Using Low-Finned Tubes with Supercritical Carbon Dioxide on the Shell Side and Water on the Tube Side*. in *ASME Turbine Technical Conference and Exposition*. 2015. Montreal, Quebec, Canada.
8. Musgrove, G., et al., *Heat Exchangers*, in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO$_2$) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Editors. 2017.