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High Effectiveness, Compact, High Pressure and Low Cost Recuperator for Super-Critical CO_2 Power Cycles

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Dr. Kelly, President and founder of Altex, has over 36 years of experience in fuels, combustion, power systems and thermal management research, development and deployment. Innovative systems developed by Dr. Kelly have been implemented in the utility, industrial process, commercial, semiconductor and solar industries. He received his BS in Mechanical Engineering from the Cooper Union of New York, MS in Nuclear Engineering from the Massachusetts Institute of Technology (MIT), and PhD in Aeronautics and Astronautics from the Polytechnic Institute of New York University.

ABSRACT

Closed Brayton super-critical CO_2 power cycles are well suited to waste heat bottoming cycles due to their increased efficiency and compactness relative to Rankine steam bottoming cycles. Since waste heat applications would be retrofits, the power system compactness is important. To achieve high efficiency, these power cycles require high pressure recuperative type heat exchangers of substantial heat duty. Current Printed Circuit Heat Exchangers (PCHE), originally developed for high pressure gas and oil applications, can be used as recuperators, but costs are higher than desired. A purpose-built high pressure and effectiveness recuperator is being developed by Altex to provide the reliability, compactness, performance and pressure capability of current recuperators, but at a reduced cost. This paper will report test results that demonstrate the heat transfer performance of this special design. For the baseline smooth channel case, this design can reduce recuperator volume by over 45% and weight by over 54% versus conventional PCHE approaches for the same heat duty. By reducing weight 54%, material costs will be reduced by a similar amount. Using the tested surface enhancements will lead to further reductions. Also, part count and number of joints are reduced by over 75% versus current designs, which also leads to lower cost. In addition, a load-assisted vacuum brazing fabrication process will be described that, along with reduced volume and weight for the special design, results in reduced cost. Current small test article fabrication costs are below larger PCHE production costs. Compared to a PCHE of the same heat duty, a cost reduction of over 50% is projected for this design under production.

INTRODUCTION

Brayton power cycles that use Supercritical CO_2 ($ScCO_2$) working fluid have the potential for higher efficiency than classical Rankine based steam power cycles [1]. Furthermore, at the high pressures required for $ScCO_2$ operation, fluid densities are very high and component sizes and footprint can be substantially reduced. Given the high base pressure with $ScCO_2$, the cycle pressure ratios are limited and recuperative heat exchangers are required to maximize cycle efficiency. In the case of waste heat driven cycles, the recuperative heat duty is in the range of 100 % greater than the electrical power output, with fossil, concentrating solar and nuclear-based cycles needing 520% higher heat duties than the electrical power output. Printed Circuit Heat Exchangers (PCHE), which have been developed for very high pressure oil, gas and chemical industry heat exchanger application, have been the most widely used recuperative type heat exchangers for $ScCO_2$ power cycle development testing [2]. PCHEs are created by chemically etching small channels in thin metal plates, with an example of the construction of a counter-flow recuperative type heat exchanger using multiple stacked plates shown in Figure 1 [3].

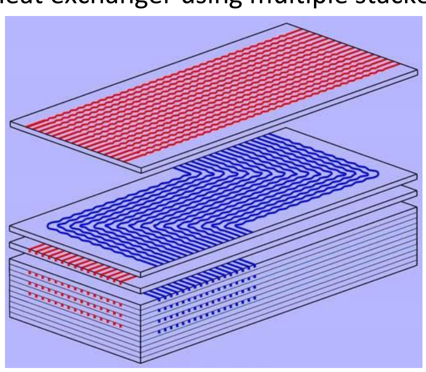

Figure 1 – Chemically Etched Channels in Stacked Plates

For clean fluids, these channels can be created at sizes below 0.4 mm, which produces high heat transfer coefficients. To create the high heat duties needed for power cycles, many plates are stacked together and diffusion bonded in a vacuum furnace, resulting in a single block structure with thousands of channels, as illustrated by the cross-section picture shown in Figure 2 [3].

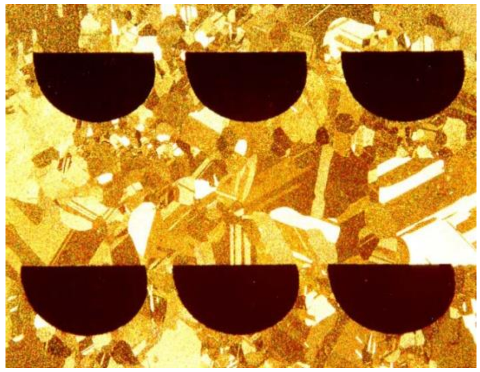

Figure 2 – Diffusion Bonded PCHE Cross-Section Picture

While robust heat exchangers can be produced for $ScCO_2$ recuperator applications, these PCHE type heat exchangers are high in cost due to both the cost of creating chemically etched channels and the diffusion bonding process. To effectively diffusion bond a stack of plates, the plate surface must have a high level of flatness and be cleaned of all contaminants. A high load of 4,000 psi must be applied in the furnace at temperatures that are near the melting temperature of the base material for several hours [4]. This process requires stack structures of high solidity that are stable in the furnace under high temperature conditions, which is a good fit for very high pressure (e.g. 9,000 psi) oil, gas and chemical applications. However, for $ScCO_2$ power cycle applications, where 20% to 30% of the plant cost might be PCHE recuperators, lower costs are needed to improve the economic competiveness of these cycles relative to the current Rankine power cycles.

To reduce recuperator cost, Altex is developing and testing the High Effectiveness Low Cost (HELC) recuperative heat exchanger that is purpose designed and built for the lower peak pressure (e.g. 3,500 psi peak pressure versus 9,000 psi for oil, gas and chemical) $ScCO_2$ application using materials, design, fabrication and bonding processes that will result in lower cost at the compactness and performance needed to meet power cycle specifications. In this paper, the progress toward developing a 500 KWt HELC test article is described [5]. To date, multiple 30 KWt test articles have been fabricated and tested to reduce the technical risk when fabricating the 500 KWt test article. In 2016, it is expected that the 500 KWt article will be fabricated and the integrity and performance tested. Following successful tests of the 500 KWt article, work can then be initiated on even larger-scale units. Ultimately, HELC capacities of 15 MWt and 3,100 MWt capacities would have to be created for 7.5 MWe waste heat and 500 MWe utility-scale $ScCO_2$ power cycle applications, respectively. In these cases, multiple HELC modules would have to be manifolded together to meet the needed recuperative heat duties.

HELC DESIGN APPROACH, ANALYSIS AND TESTING

As a purpose-built $ScCO_2$ recuperator, HELC needs to target pressures of 3,500 psi with a waste heat application maximum temperature of 360 C, with other applications of up to 700 C maximum temperature [2]. The unit must meet ASME pressure vessel code requirements that employ safety factors for both pressure and temperature that limits maximum stress in the structure. Given the temperature of the waste heat application, a HELC could be constructed of 316 stainless steel material and meet this static limit with a solidity of 52.6**%,** considering rectangular channels with a hydraulic diameter of 1.0 mm. While this static loading limit can be met by HELC, thermal cycling of the unit can create internal stresses that can limit the lifetime of the unit. In the case of PCHEs, the high solidity of the structure under thermal cycling can create thermally induced stresses near the surface on the order of the yield stress for 316L SS, which can reduce the life of the unit [2]. To address this issue, HELC is designed with a core that has significant flexibility with the potential to limit thermally induced stresses and fatigue, thereby improving lifetime. This capability to limit thermally induced stresses is presently being investigated by Altex.

As described above and illustrated in Figure 2, PCHE heat exchangers have high solidity. Also, the high channel surface areas needed for power cycles require substantial stacks of chemically etched plates that drive up costs. With HELC, the needed large surface area is produced by inserts fabricated from inexpensive material that forms small rectangular channels. By utilizing this approach, the heat transfer surface area per volume is increased versus the PCHE channel configuration illustrated in Figure 2. Table 1 compares the PCHE and HELC channels on a per-volume basis for the same hydraulic diameter. Considering a smooth wall channel and the same ScCO2 fluid and conditions, matching the hydraulic diameter will provide a similar heat transfer coefficient. Because of the geometrical differences in PCHE versus HELC, this similar heat transfer coefficient will yield different weight and volume parameters to meet the same heat duty needs for PCHE and HELC. As shown in Table 1, HELC has a lower solidity and a much higher area per volume than the PCHE. This leads to advantages in weight and volume per heat transfer surface area. For the same hydraulic diameter, heat transfer coefficient and fluid conditions, heat transfer will be proportional to the surface area. Therefore, from Table 1, the HELC would be 54.7% lower in weight and material cost than a PCHE for the same heat transfer. In addition, the HELC volume would be 45.2% lower than that for a PCHE.

Table 1 – Comparison of HELC and PCHE Channels

Heat Exchanger	Solidity	Area/Volume	Weight/Area	Volume/Area
	(%)	(ft2/ft3)	(lbm/ft2)	(ft3/ft2)
PCHE	63.6	447	.697	.00223
HELC	52.6	816	.315	.00123
HELC/PCHE	.893	1.82	.453	.548

Besides the better weight, material cost and volume per surface area characteristics, the HELC also has the advantage of 78% fewer bond joints and parts per volume that should also help to reduce cost.

In order to contain the inserts and separate the fluids, the HELC design includes separation plates of the proper thickness and frames that contain the inserts and together with the plates form the inlet and outlet manifolds. These plates and frames, illustrated in Figure 3, can be constructed with the needed thicknesses to address both core and manifold pressure requirements, with the completed 30 KW article included in Figure 4 [6].

Figure 3 – HELC Plate and Frame Construction

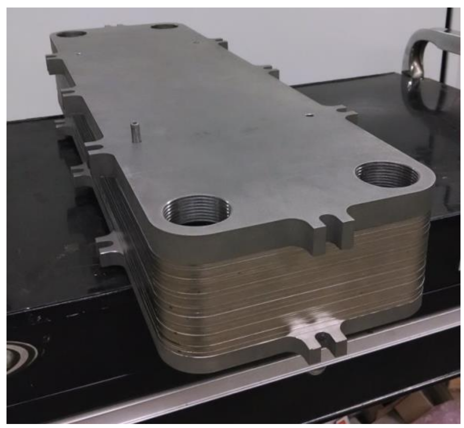

Figure 4 – HELC 30 KWt Test Article with Early Inserts

As noted above, the PCHE stack diffusion bonding process requires high quality surface flatness and cleanliness, with the substantial solidity supporting the high compression loads needed for good diffusion bonding [4]. Furthermore, for the large heat duties needed for $ScCO_2$ power cycles, the PCHE modules can be very large, requiring careful control of platen loading to ensure even pressure over the large article during bonding. In addition, with the very high temperature required for diffusion bonding and the large articles, the heat up and temperature uniformity must be carefully controlled to produce high quality bonds throughout the article. In contrast, HELC uses a load-assisted brazing process that uses the braze filler material to address surface flatness imperfections and, in particular, tolerance mismatches between plate, frame and inserts. Also, the needed HELC solidity to achieve the benefits listed in Table 1 is lower than that needed for PCHE because of the order of magnitude lower furnace loading used with HELC brazing process versus the diffusion bonding used with PCHEs.

Another potential advantage for HELC is the ability to inexpensively form surface features in the inserts to enhance heat transfer at acceptable pressure drop. By enhancing the heat transfer per surface area, the volume and material use can be further reduced, which reduces cost and increases compactness that is particularly beneficial for space limited waste heat retrofit applications. Also, with a smaller article, the article temperature non-uniformities in the bonding furnace will be reduced, making joint quality and strength more uniform.

Using the Altex heat transfer and pressure drop test apparatus, several surface features were tested to identify high potential candidates for HELC. The heat transfer and pressure drops, using heated air, were converted to J (Colburn heat transfer coefficient) and f factors that have been used by many other researchers to characterize surface feature heat transfer enhancement performance [7]. Figure 5 gives a comparison of smooth channel, and surface heat transfer enhancement features 1, 2 and 3.

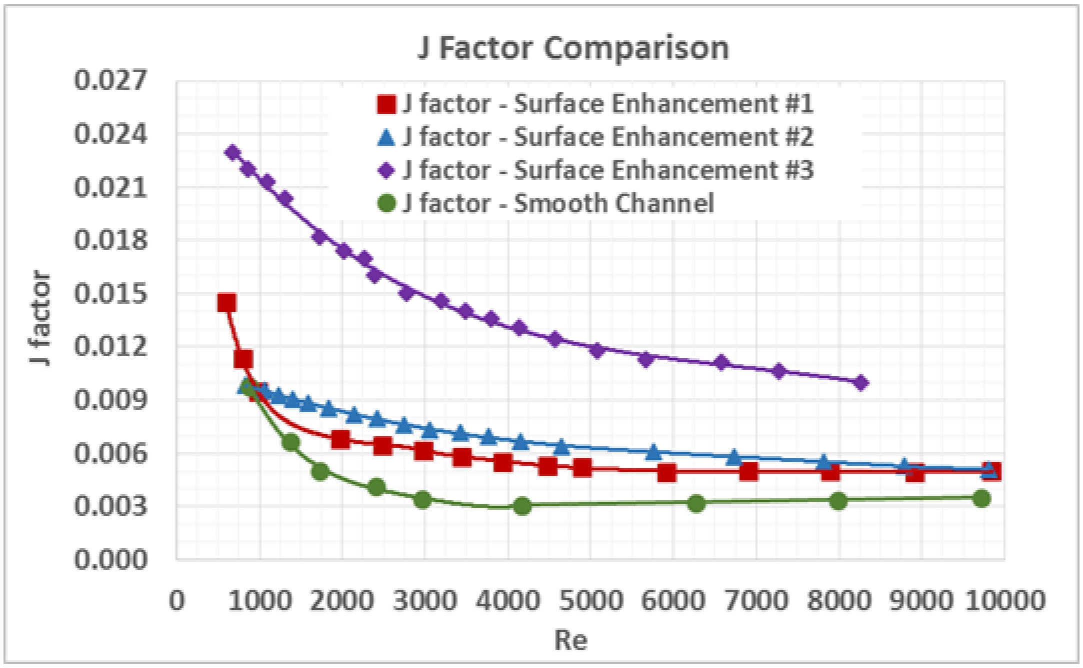

Figure 5 – Comparison of Smooth and Surface Feature Enhancements 1, 2 and 3 for HELC

As shown, for a Reynolds number of 3,000, surface features 1, 2 and 3 have approximately 71%, 100% and 342% higher J factors than the baseline smooth channel case. Since J is directly related to the heat transfer coefficient [8], and the heat transfer is related to this coefficient times the surface area, then for a given heat duty, features 1, 2 and 3 would further reduce the core volumes by 42%, 50% and 77%, respectively, thereby reducing core material requirements and costs by the same amounts. By implementing these surface features, the advantages of the smooth channel HELC design presented in Table 1 would be increased. In addition, with the more compact units, bonding furnace temperature non-uniformities will be reduced and bonds optimized.

While improving heat transfer through surface features is an important objective for HELC, these improvements should not be achieved at the expense of excessive pressure drop that can reduce power cycle efficiency. Many conventional approach surface features enhance heat transfer versus a smooth channel wall, but enhance pressure drop even more. In these cases, the thermal efficiency, which is equal to J/f for fixed properties and velocities, is decreased relative to the more efficient smooth channel wall case. However, surface features 1, 2 and 3 were configured to maintain high efficiency while providing up to 342**%** heat transfer augmentation. This is illustrated in Figure 6, where both cases with surface features have J/f values that are relatively consistent with the smooth channels, indicating that a more compact HELC with the needed heat duty would have a similar pressure drop and pumping power need to the larger smooth channel case that achieves the same heat transfer. This maintenance of pressure drop and cycle efficiency under more compact packaging is advantageous. It should be noted that some conventional heat transfer enhancement surface features cannot match the efficiency of those given in Figure 6, with J/f results from the literature [8] compared with base smooth channel and surface features 1, 2 and 3 in Table 2 at a Reynolds number of 3,000.

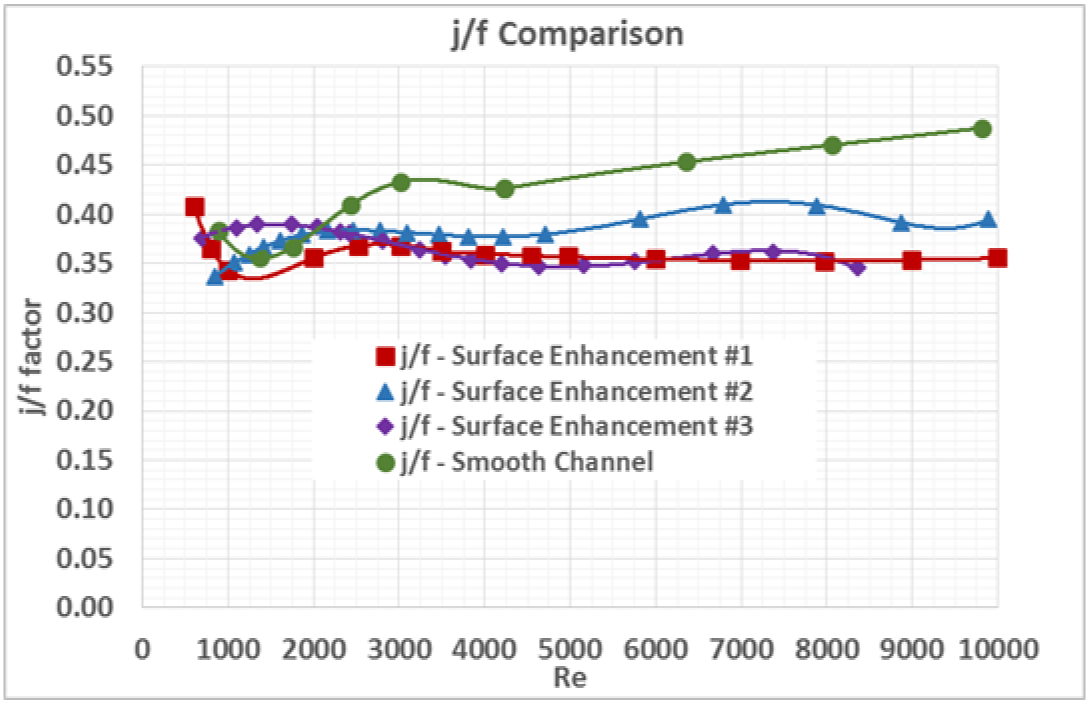

Figure 6 – Comparison of J/f for Smooth Channel and Surface Features 1, 2 and 3 Cases

Table 2 – Comparison of Special Surface Feature and Conventional Cases with the Smooth Channel Baseline

Surface	**J**	**J/f**	**Efficiency Reduction versus Smooth Channel (%)**
Smooth Channel Baseline	**.0033**	**.43**	**--**
Surface Enhancement 1	**.0062**	**.365**	**15.2**
Surface Enhancement 2	**.0075**	**.380**	**11.6**
Surface Enhancement 3	**.0148**	**.365**	**15.2**
Louvered Surface	**.009**	**.225**	**47.7**
Wavy Surface	**.0105**	**.202**	**53.0**

The higher efficiency of surface features 1, 2 and 3 versus conventional enhancements is clearly shown in this comparison. Besides higher efficiency, surface feature 3 has the highest heat transfer coefficient

J of all the cases, with 41% higher performance than the wavy surface. These cases all used air as the working fluid. $ScCO_2$ will be much denser, with maximum densities approaching water density levels at the highest pressure of 3,500 psi, with $ScCO_2$ at 54 lbs/cf versus 64 lbs/cf for water. In addition, the specific heat, viscosity and Prandtl number are very different from the air test results. Also, depending on the channel configuration and scale, the changing $ScCO_2$ density with temperature could create buoyancy and secondary flow effects that can change the heat transfer and pressure drop performance [9]. Nevertheless, the ordering of J and J/f results exhibited in Figures 5 and 6 are not expected to be changed by shifting to $ScCO_2$.

To date, two smooth channel 30 KWt HELC test articles have been tested using water that has a high density similar to that for $ScCO_2$ operation. Using electrical heaters to produce hot water at up to 200 F and 30 psi for the hot side of the recuperator and using a chiller to create 70 F and 30 psi water for the cold side, the heat transfer and pressure drop performance of HELC with the early insert design was determined. Figure 4 is a picture of the 30 KWt HELC test article with early design inserts that used channels with a hydraulic diameter of 1.82 mm. It should be noted that this configuration used only two layers (two high pressure and two low pressure sublayers) to limit test article expense, but used thick end plates that would be the same as those used in the multilayer 500 KWt test article. To monitor temperature and pressure J type thermocouples and WIKA pressure transducers were utilized. Flow was measured by Blancett turbine flow meters with the data acquired every two seconds by a National Instruments DAQ hardware with LabVIEW software. Figure 7 gives a comparison of the measured results compared to the Altex performance model that is based on an Ntu approach that uses J and f factors [8]. This modeling approach is well established and can readily use J and f factors from tests or literature to support HELC design efforts [8]. For the test data and model comparisons, the smooth channel J and f factors from Figures 5 and 6 were utilized for the two smooth channel test article cases. Besides incorporating HELC geometric and metal material properties, the model can include various fluid properties to cover water, oil, $ScCO_2$ or other fluids of interest. As shown in Figure 7, the heat transfer increases with water flow rate. Heat transfer levels are consistent with the design target and test results are consistent within 13% with the model results. This supports the validity of the model.

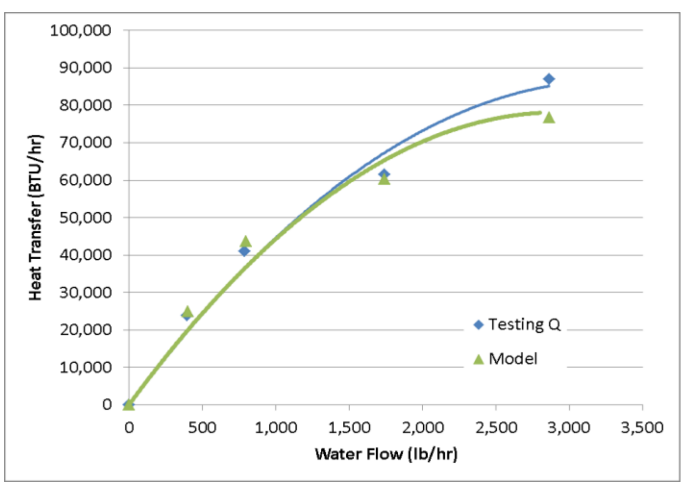

Figure 7 – Comparison of Early Inserts HELC Heat Transfer Test Data and Model Results

Pressure drop test and model results are compared in Figure 8. As shown, pressure drop test results are consistent within 10%, which also supports the validity of the model.

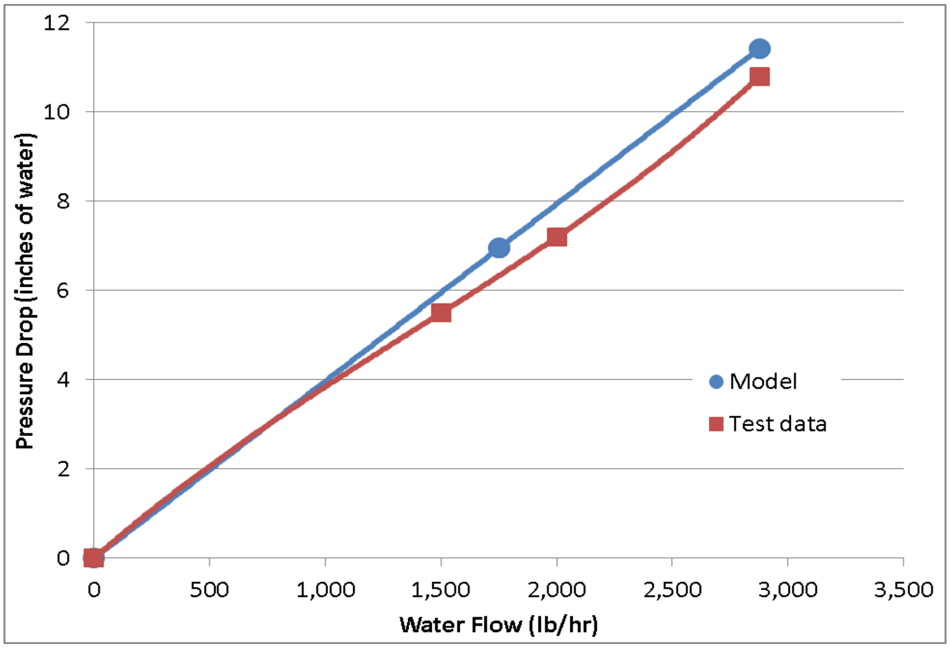

Figure 8 – Comparison of Early Inserts HELC Test and Model Pressure Drop Results

Following the early insert HELC article test, the HELC insert and manifold designs were updated and the new 30 KWt unit test article pictured in Figure 9 was fabricated. As shown, the new design has offset inlets and outlets to provide easier manifolding of multiple HELC units in an array for large recuperator heat duties. The new insert design utilized channels with 1.37 mm hydraulic diameter.

Figure 9 – Updated 30KWt HELC Test Article

As with the prior HELC article tests, heated water was utilized in the performance tests. Figure 10 gives a comparison between test and model heat transfer results. As with the earlier tests, this longer length but single layer test article gives 29 KWt heat transfer as anticipated. In addition, the consistency of test and model results supports the validity of the model for design purposes.

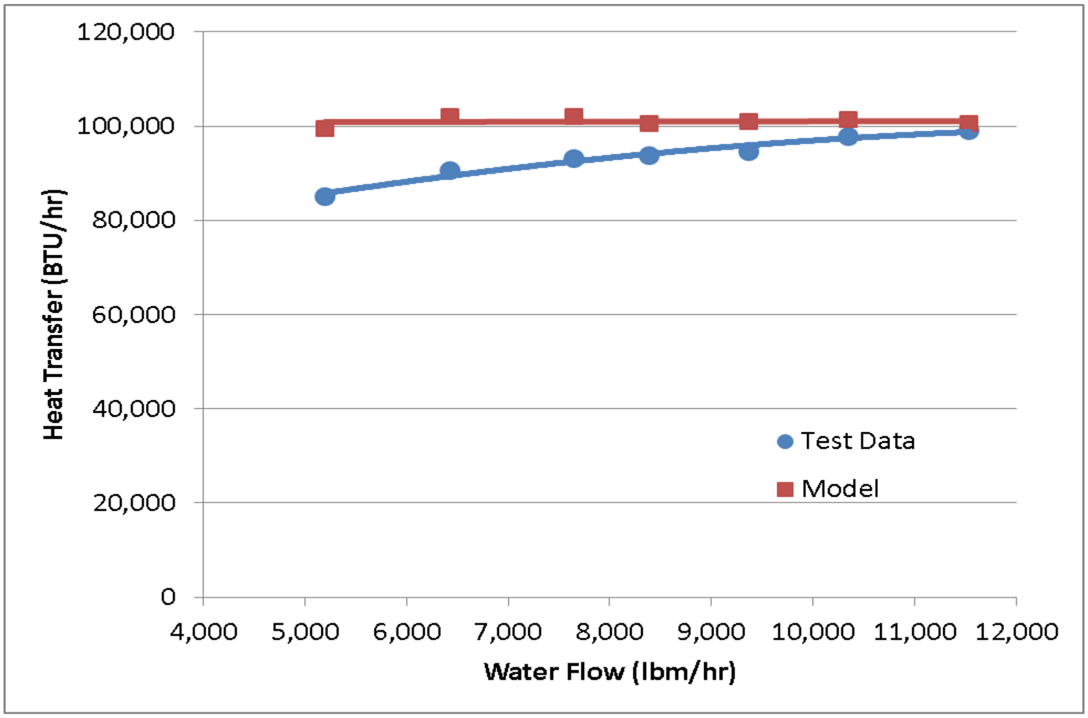

Figure 10 – Comparison of Updated 30 KWt HELC Article Test and Model Heat Transfer Results

CONCLUSIONS

From the basic design approach differences, the HELC is expected to have higher heat transfer surface area per volume and lower weight per surface area, which should reduce material costs. Relative to a PCHE using the same smooth channels of the same channel hydraulic diameter and achieving the same heat duty, HELC would have 54.7% and 45.2% lower weight and volume, respectively. This will reduce material cost by 54.7%. Also, due to less stringent surface flatness and cleanliness and reduced furnace bonding temperature and time versus diffusion bonding, the load assisted braze process used in HELC should save costs relative to PCHEs. Lastly, the 78% lower part and joint count with HELC should also help to lower cost. Using a performance test apparatus, three HELC surface heat transfer enhancement approaches were identified and tested that had 71%, 100% and 342% higher heat transfer coefficients than the baseline smooth channel case that was also tested. Importantly, these very substantial increases in heat transfer coefficients were achieved at thermal efficiencies (i.e. heat transfer per flow power needed to drive the heat transfer) similar to the highly efficient, but lower heat transfer potential, smooth channel case. Using the J factors from the test results it is estimated that the surface enhancements 1, 2 and 3 would reduce the smooth channel HELC heat exchanger volumes by a further 42%, 50% and 77%, respectively, with similar reductions in heat exchanger weight and material cost. To support 500 KWt recuperator design and fabrication, two 30 KWt articles were built and tested. The hot water heat transfer test results for both articles were consistent with the J and f factor model predictions, supporting the use of this model for heat exchanger design, particularly when the new J and f factors are incorporated into the model.

FUTURE ACTIONS

Destructive testing of the 30 KWt articles are planned to evaluate the braze bond integrity and a final 50 KWt test article will be built and tested to demonstrate HELC manufacturing at small scales. Success with this article will lead to the design, fabrication and test of the 500 KWt test article in 2016.

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