ANL/NE-C2016-16142

High Efficiency Heat Exchanger for High Temperature and High Pressure Applications

Final CRADA Report

Nuclear Engineering Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (http://www.osti.gov/scitech/)

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

ANL/NE-C2016-16142

High Efficiency Heat Exchanger for High Temperature and High Pressure Applications

Final CRADA Report

prepared by
James J. Sienicki, Qiuping Lv, and Anton Moisseytsev

Nuclear Engineering Division, Argonne National Laboratory

Participants: CompRex LLC

September 29, 2017

This page intentionally left blank

Argonne NATIONAL LABORATORY

Non Proprietary

Final CRADA Report

Date: September 29, 2017

CRADA Number: 2016-16142

CRADA Title: High Efficiency Heat Exchanger for High Temperature and High Pressure Applications

CRADA Start/End Date: September 12, 2016 to September 30, 2017

Argonne Dollars: $300,000

Participant Dollars: $75,000

Argonne PI: James J. Sienicki

Participant(s):

CompRex, LLC — $75,000
Name — Participant Dollars

1740 Eisenhower Drive , De Pere WI 54115
Complete Address

______ $______
Name — Participant Dollars

______
Complete Address

______ $______
Name — Participant Dollars

______
Complete Address

DOE Program Manager: Tom Miller

Summary of Major Accomplishments:

1 Background on CompRex

CompRex, LLC (CompRex) specializes in the design and manufacture of compact heat exchangers and heat exchange reactors for high temperature and high pressure applications. CompRex's proprietary compact technology not only increases heat exchange efficiency by at least 25 % but also reduces footprint by at least a factor of ten compared to traditional shell-and-tube solutions of the same capacity and by 15 to 20 % compared to other currently available Printed Circuit Heat Exchanger (PCHE)

Summary of Major Accomplishments:

solutions. As a result, CompRex's solution is especially suitable for Brayton cycle supercritical carbon dioxide (sCO2) systems given its high efficiency and significantly lower capital and operating expenses. CompRex has already successfully demonstrated its technology and ability to deliver with a pilot-scale compact heat exchanger that was under contract by the Naval Nuclear Laboratory for sCO2 power cycle development. The performance tested unit met or exceeded the thermal and hydraulic specifications with measured heat transfer between 95 to 98 % of maximum heat transfer and temperature and pressure drop values all consistent with the modeled values. CompRex's vision is to commercialize its compact technology and become the leading provider for compact heat exchangers and heat exchange reactors for various applications including Brayton cycle sCO2 systems.

One of the limitations of the sCO2 Brayton power cycle is the design and manufacturing of efficient heat exchangers at extreme operating conditions. Current diffusion-bonded heat exchangers have limitations on the channel size through which the fluid travels, resulting in excessive solid material per heat exchanger volume. CompRex's design allows for more open area and shorter fluid proximity for increased heat transfer efficiency while sustaining the structural integrity needed for the application.

CompRex is developing a novel improvement to its current heat exchanger design where fluids are directed to alternating channels so that each fluid is fully surrounded by the opposing fluid. As compared to similar existing compact heat exchangers, the new design converts most secondary surface area to primary surface area, eliminating fin inefficiencies.

CompRex requests that all technical information about the heat exchanger designs be protected as proprietary information. To honor that request, only non-proprietay summaries are included in this report.

2 Objectives

The objectives of this work are:

1) To carry out Computational Fluid Dynamics (CFD) calculations modeling a number of different CompRex heat exchanger designs specified by CompRex;
2) To develop a Fortran computer code that is simpler than CFD but effectively modeling the improved CompRex heat exchanger designs and calculating the heat exchange and pressure drop perfromance of the heat exchanger designs;
3) To use the simpler Fortran computer code to develop preliminary optimized sodium-to-CO2, CO2-to-CO2 high temperature recuperator, CO2-to-CO2 low temperature recuperator, and CO2-to-water cooler heat exchanger designs for the Advanced Fast Reactor (AFR)-100 Sodium-Cooled Fast Reactor (SFR) sCO2 Brayton cycle power converter [1 and 2]; and
4) To compare the performance of the CompRex designs for the AFR-100 sCO2 Brayton cycle power converter with that of more common Printed Circuit Heat Exchanger (PCHE)-type designs.

3 Heat Transfer and Pressure Drop Correlations

For the features of the proprietary CompRex heat exchanger configuration, Argonne identified correlations for one-dimensional flow from the open literature that can be incorporated into the Fortran computer code developed by Argonne to approximately model the heat transfer and pressure drop performance of the heat exchanger designs. Those references cannot be included in this report as they would reveal features of the configuration.

4 Computational Fluid Dynamics Calculations

At the request of CompRex, Argonne carried out CFD calculations of ten different heat exchanger designs specified by CompRex. The Fluent CFD code was used as Fluent is also used at CompRex. The calculations model the flow of supercritical CO2 at a lower pressure than the CO2 in a sCO2 Brayton cycle. For each design, calculations were performed for three different Reynolds numbers.

5 Procurement of Heat Exchangers for Testing

Six small-scale compact diffusion-bonded heat exchangers encompassing three different designs specified by CompRex were procured by Argonne from a vendor. The heat exchangers were fabricated with a lower design pressure than required for use with a sCO2 Brayton cycle. This relaxes the design pressure that each design must withstand. Three of the heat exchangers encompassing the three different designs are to be used for thermal hydraulic testing of their heat exchange and pressure drop performance using supercritical CO2. The other three are to be subjected to burst testing. The data from the thermal hydraulic tests is intended to provide a basis to test and validate the Argonne CFD and simpler Fortran computer code calculations of thermal hydraulic behavior. The burst tests of three different designs are intended to validate the structural design calculations carried out by CompRex.

6 Fortran Computer Code

A Fortan computer code was developed by Argonne to calculate the heat transfer and pressure drop performance of the CompRex heat exchanger designs. The virtue of this new computer code is that it is much simpler than a CFD code and can be used to carry out many calculations for design analysis and optimization. The code models the fluid channels in the core as well as in the flow distributors. The code calculates one-dimensional conditions inside of multiple channels thereby producing a two-dimensional distribution of thermal hydraulic conditions. Essential features of the design are modeled through the incorporation of appropriate heat transfer and pressure drop correlations. The correlations apply to ordinary fluids which are assumed to include carbon dioxide under the conditions of interest to sCO2 Brayton cycles. The correlations currently do not include liquid metals such that care must be taken in interpreting results from calculations where one of the fluids is sodium.

7 Code Testing and Validation

To provide confidence in results calculated for the CompRex designs, the CFD model and the simpler Fortran computer code need to be compared with data from thermal hydraulic testing of the three heat exchangers using supercritical CO2. CompRex has not yet provided this data to Argonne. Consequently, Argonne has not been able to test and validate either the CFD model or the Fortran computer code. In the case of the Fortran computer code, testing is essential to determine if the heat transfer and frictional correlations implemented into the code simulate the CompRex design sufficiently well. If they do not, then it may be necessary to develop improved correlations from analysis of the data using the code.

Summary of Major Accomplishments:

In the absence of data, the simpler Fortran computer code could be tested and verified through comparison with the results of one or more of the CFD calculations. This has not yet been done.

Due to the lack of code testing and validation, application of the Fortran thermal hydraulic model to the CompRex heat exchanger designs currently involves uncertainty.

8 Investigation of Performance of CompRex Heat Exchanger Designs in a sCO2 Brayton Cycle

The Fortran computer code was applied to determine the dimensions and conditions for the CO2-to-CO2 high temperature recuperator, CO2-to-CO2 low temperature recuperator, sodium-to-CO2 heat exchanger, and CO2-to-water cooler of the AFR-100 sCO2 Brayton cycle power converter. To investigate whether the CompRex designs offer any benefits relative to traditional Printed Circuit Heat Exchanger (PCHE) technology, the CompRex designs were required to match the performance of the PCHE-type designs previously developed for the AFR-100 sCO2 Brayton cycle power converter. The CompRex designs were not optimized to reduce the Nuclear Power Plant (NPP) cost per unit output electrical power ($/kWe) as were the PCHE designs. Due to the lack of validation of the new Fortran computer code, the results of this investigation must be viewed as preliminary and potentially subject to significant uncertainty. It was found that CompRex heat exchangers that match the PCHE performance have similar total volumes to the PCHE heat exchangers with the volumes of the CompRex high temperature and low temperature recuperators somewhat larger than the PCHE high and low temperature recuperators.

9 Recommended Future Work Under a Future GAIN Award

CompRex with strong support from Argonne prepared a proposal for continuation of this work under a second GAIN award under the second year of the GAIN Program. The requested amount of $ 500,000 versus $ 300,000 for this award would have enabled significant additional progress toward commercialization. Unfortunately, that proposal was not awarded. CompRex and Argonne intend to submit a proposal to continue this work under the third year of GAIN. This report provides documentation of the accomplishments during this Project which is viewed as Phase 1 of a longer development effort. CompRex with strong support from Argonne will again submit a Request for Assistance under the third year of the GAIN Program to continue the work under a second phase.

In Phase 2 of this project proposed under a future Nuclear Energy Voucher program, CompRex will again work with Argonne to continue the development of the compact heat exchanger technology. CompRex will utilize Argonne's unique modeling and analysis capabilities, specifically, the new heat exchanger computer code that was developed at Argonne during Phase 1. During Phase 2, the new Fortran computer code developed at Argonne during Phase 1 will be compared with data obtained from testing of the small-scale heat exchangers procured by Argonne during Phase 1. If warranted, the code modeling will be improved, and the models and code will be validated with the small-scale data. The modeling will be implemented into Argonne's Plant Dynamics Code (PDC) which is the current state-of-the-art computer code for plant dynamic analyses of sCO2 Brayton cycles. The PDC will be utilized to determine further refined and optimized heat exchanger designs for the sodium-to-CO2 heat exchangers, high temperature recuperator, low temperature recuperator, and cooler for a sCO2 Brayton cycle coupled to the Argonne AFR-100 SFR design. Argonne will use its expertise including knowledge of the minimum sodium channel size for sodium-to-CO2 heat exchangers to permit efficient draining of intermediate sodium and the avoidance of inadvertent sodium plugging in the event of air ingression into the intermediate sodium, and the minimum CO2 channel size to avoid significant channel occlusion by

Summary of Major Accomplishments:

oxide layers formed by oxidation of the structural walls. The heat exchanger designs will be optimized to reduce the nuclear power plant cost per unit output electrical power ($/kWe) or the Levelized Cost of Electricity ($/MW·hr).

Based upon the optimized heat exchanger designs for the sCO2 Brayton cycle, a reduced-scale heat exchanger will be designed for testing under prototypical sCO2 Brayton cycle conditions and procured. Its heat transfer and pressure drop performance shall first be tested at a CompRex-affiliated laboratory after which it will be shipped to Argonne for further testing with CO2 and sodium under prototypical conditions. Design of a new testing facility for CO2-to-CO2 and sodum-to-CO2 heat exchangers at Argonne shall be carried out, parts and components procured, and assembly carried out. If completed, testing with the heat exchanger shall be initiated.

As part of Phase 2, CompRex will design and manufacture one test heat exchanger and one demonstration heat exchanger, each with the full footprint (at reduced height). The purpose of the exchanger fabrication is to prove the technical feasibility of all aspects of the manufacturing steps of the large exchanger, address any concerns for the full-scale manufacturing, perform destructive testing on the test unit for structural integrity confirmation, and provide the demonstration unit for performance testing at Argonne. The main limitation in the manufacture of diffusion-bonded heat exchangers is furnace size. One unit will become the test heat exchanger for destructive testing, while the other two will be welded together to produce a larger exchanger for demonstration purposes. The manufacturing steps that will be practiced and proven are: (1) etching of the large-scale metal sheets, (2) bonding the sheets to produce the individual units, (3) welding the bonded units to produce larger height units, and (4) welding headers and nozzles for easy connection into the process. Upon completion of manufacturing, CompRex and Argonne will have a solid understanding of fabrication cost, manufacturing time and schedule, and will have addressed the critical steps in the manufacturing process. Furthermore, after performance testing and validation by Argonne (while working closely with CompRex), a better understanding of heat exchanger size reduction, efficiency gains, and cost savings over other compact diffusion-bonded heat exchangers will be realized.

As a domestic U.S. company, CompRex's innovative compact heat exchanger technology will be directly applicable to the sCO2 Brayton cycle under development by DOE Nuclear Energy as a heat source (e.g., sodium)-to-CO2 heat exchangers, high temperature recuperators, low temperature recuperators, and coolers that can be utilized with SFRs as well as other advanced nuclear power reactors (e.g., LFR, HTGR, Liquid Salt), and nuclear reactors driving submarines and naval surface ships. CompRex's technology can reduce the cost of these components thereby further improving the energy generation economics and economic competitiveness of sCO2 cycles relative to Rankine steam cycles and gas Brayton cycles. The sCO2 Brayton cycle eliminates the need to accommodate sodium-water reactions thereby enhancing SFR safety as well as improving economic competitiveness. The sCO2 Brayton cycle is also being developed by DOE for fossil energy and solar energy applications. For fossil energy applications, it can support reduced emissions through greater efficiency thereby reducing environmental impact. The new heat exchangers can also be utilized for other nuclear energy applications such as compact and less costly sodium-to-sodium intermediate heat exchangers for SFRs or recuperators and helium coolers for HTGRs. The heat exchanger technology is also applicable to other non-nuclear markets where compactness or high efficiency is a benefit. Those markets may be greater than the nuclear market.

Acknowledgements

Summary of Major Accomplishments:

Argonne National Laboratory's work was supported by the U. S. Department of Energy Gateway for Accelerated Innovation in Nuclear (GAIN) Program under Prime Contract No. DE-AC02-06CH11357 between the U.S. Department of Energy and UChicago Argonne, LLC. The authors are grateful to Hussein Khalil (Argonne) and John Howard Jackson (Idaho National Laboratory) who manage the GAIN Program at Argonne and INL. Special thanks go to Zhijun Jia, Cindy Jia, and Hani Gadalla of CompRex. Figures were drawn by Lu Krajtl (Argonne).

References

1. J. J. Sienicki, A. Moisseytsev, and Q. Lv, "Dry Air Cooling and the sCO2 Brayton Cycle," GT2017-64042, Proceedings of ASME Turbo Expo 2017, Charlotte, NC, June 26-30, 2017.
2. J. J. Sienicki, A. Moisseytsev, and L. Krajtl, "A Supercritical CO2 Brayton Cycle Power Converter for a Sodium-Cooled Fast Reactor Small Modular Reactor," PowerEnergy2015-49185, Proceedings of ASME Power & Energy Conference 2015, ASME 2015 - Nuclear Forum, San Diego, CA, June 28-July 2, 2015.

Summary of Technology Transfer Benefits to Industry:

The Fortran thermal hydraulic computer code developed by Argonne will enable CompRex to better design compact diffusion-bonded heat exchangers.

Other Information/Results: (Papers, Inventions, Software, etc.)

A Fortran thermal hydraulic computer code modeling the specific features of the CompRex compact diffusion-bonded heat exchanger designs has been developed by Argonne.

This page intentionally left blank

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC