Cost Reduction for Advanced Integration Heat Exchanger Technology for Microreactors

DOE-NE Microreactor Program

NEUP Project 21-24226

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Advanced Reactor Modeling and Simulation

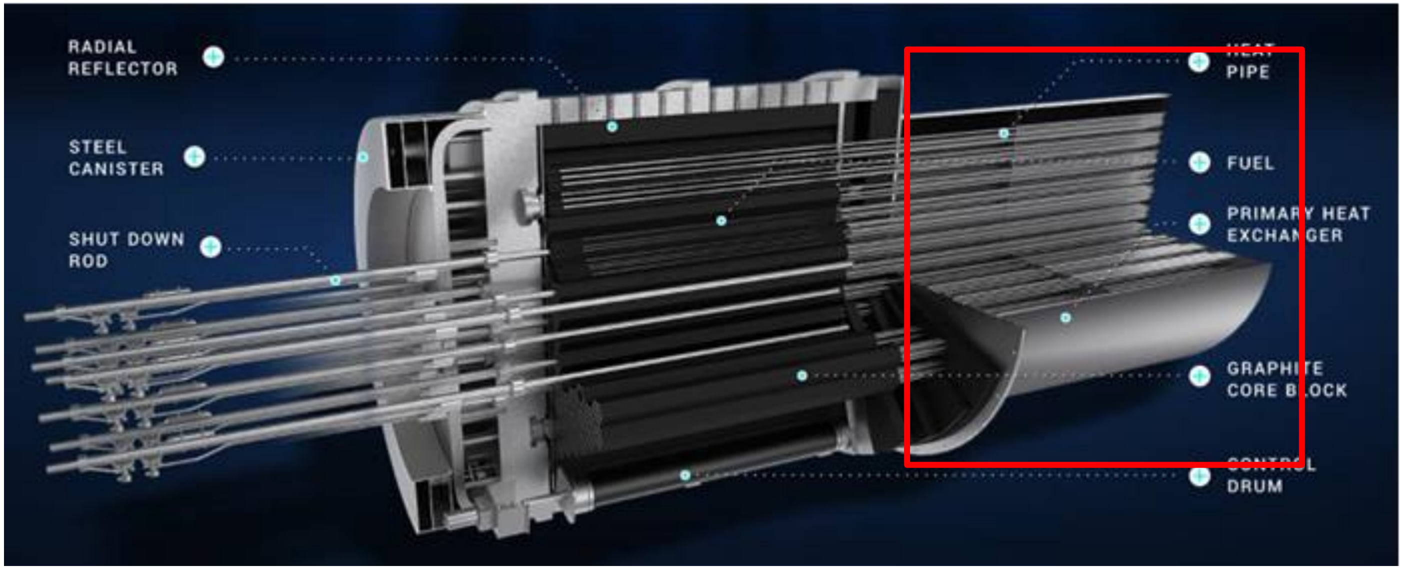
Overview

- Introduction to project and organization
- Work on Tasks 1 and 2 – development of simulation capability
  - Microreactor
  - Heat pipes
  - Cycle
  - PCHE interface heat exchanger
- Progress towards year 1 milestones
- Future work and conclusions

Interface Heat Exchanger

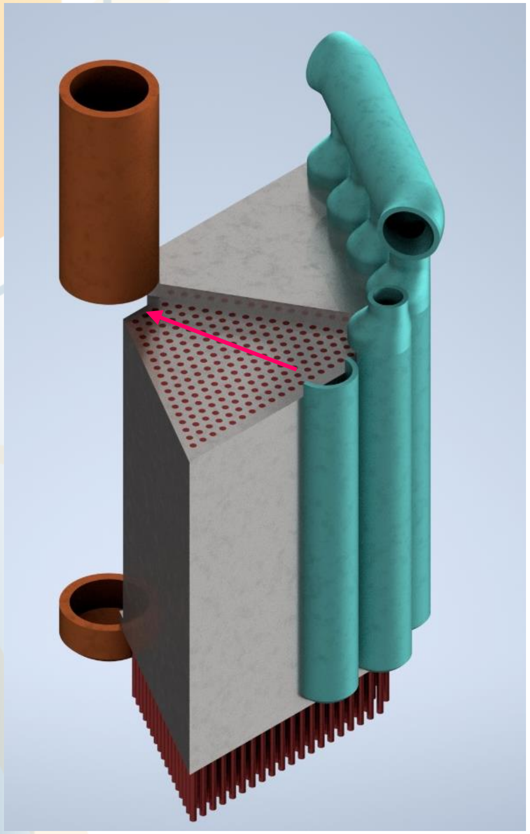
Objectives

- Development and validation of microreactor integration heat exchanger design tools
- Demonstrate potential cost-reduction/performance improvements in the context of an eVinci-like microreactor
- Obtain benchmark and validation data
- Obtain data for ASME boiler pressure vessel code case for PCHE HX in nuclear applications
- Demonstrate sub-size PCHE-based integration HX for sCO2 and air working fluids
- Train several students for nuclear industry



eVinci$^{\text{TM}}$ Micro-Reactor, Courtesy of Westinghouse Electric Company LLC

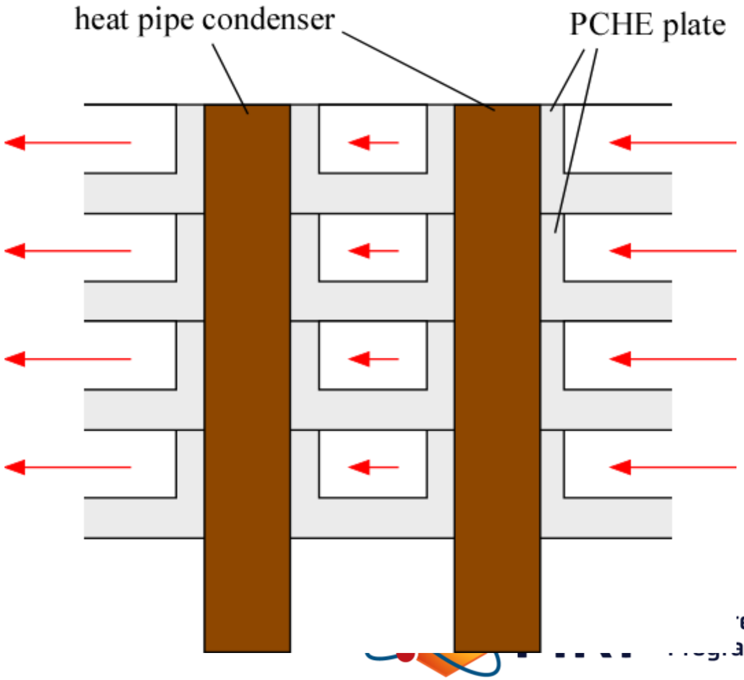
PCHE-Based Interface Heat Exchanger



Concept of a PCHE-based integration heat exchanger

Potential advantages (Morton, 2020 [6])

- Mature technology.
- Additional geometric degrees of freedom.
- Plates provide additional surface area
- Low susceptibility to single channel blockage.
- Reduced axial temperature gradient.
- Uniform condenser temperature (per heat pipe) takes advantage of the entire condenser section.
- High pressure capability of PCHE geometry.



Project Organization

Task 1: Develop balance of system models (Q1-Q4)

- Develop low-level models of the components affected by the integration heat exchanger
- Microreactor: fuel and monolith in order to predict limiting reactor hot spots and coupling between heat pipes
- Heat pipe: sodium heat pipe in order to predict thermal resistance and performance limits
- Cycle: end-use application in order to provide insight into the value of improved interface heat exchanger performance

Task 2: Develop model of PCHE-based integration heat exchanger (Q1-Q5)

- High fidelity model of the heat exchanger capable of carrying out design studies.
- Used to optimize heat exchanger subject to constraints related to loading and operating conditions.
- Develop detailed design for heat exchangers for air- and sCO_2-Brayton applications.

Task 3: Techno-economic optimization of integration heat exchanger (Q2 – Q6)

- Assess the value of PCHE-based integration heat exchanger in the context of two end-uses: air-Brayton and sCO_2-Brayton power cycles.
- Compare with alternative integration heat exchanger.
- Extension of the Economics-by-Design approach discussed in INL/EXT-21-63067 [1]

Project Organization

Task 4: Procure test articles (Q6-Q8)

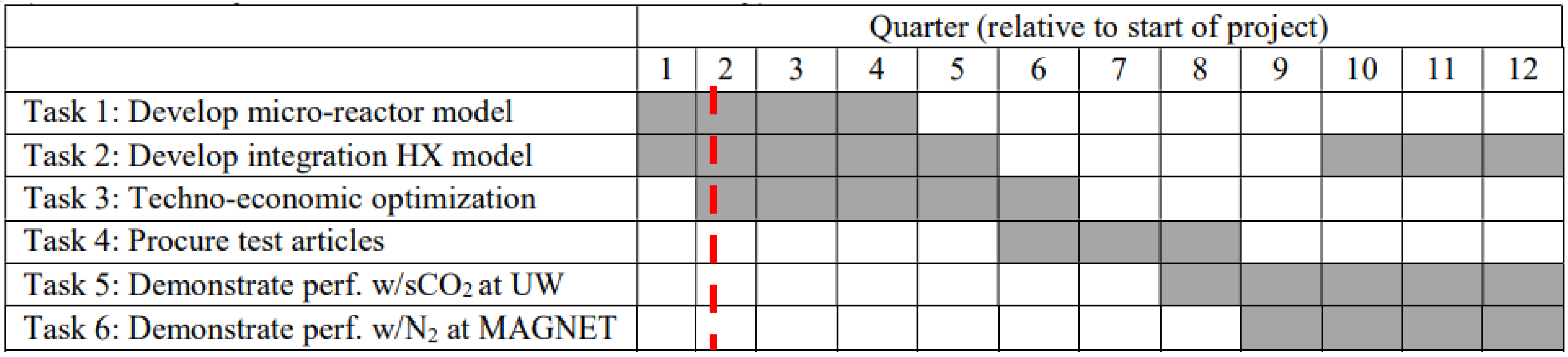
- Obtain sub-size test articles corresponding to the two designs (air and sCO_2) developed in Task 2.

Task 5: Demonstrate performance using sCO_2 at UW (Q8-Q12)

- Instrument sCO2 test article in order to characterize thermal-hydraulic performance.
- Optical sensors will be used to obtain details regarding temperature distribution along plates.
- Install in sCO_2 loop at UW.

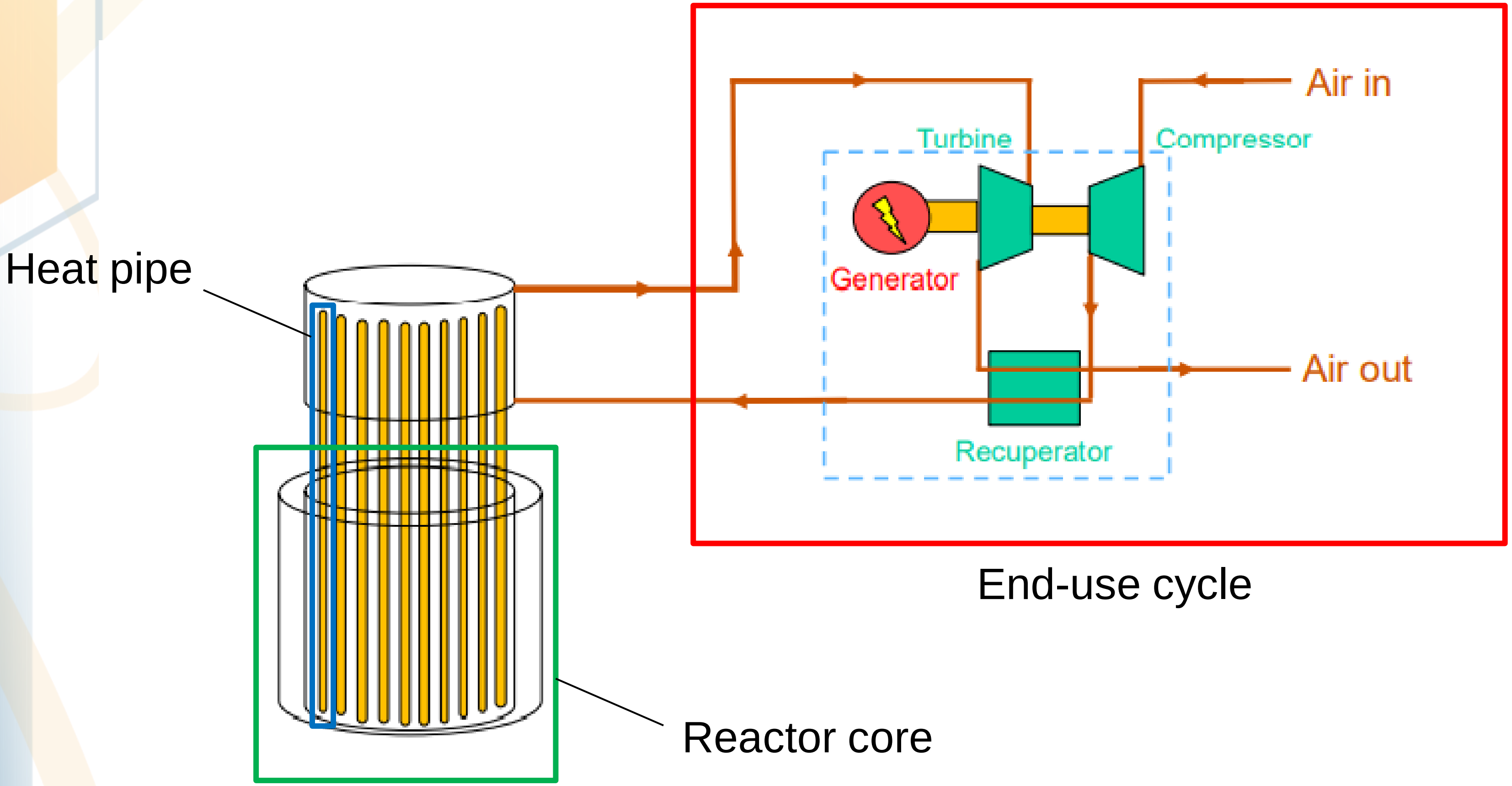
Task 6: Demonstrate performance using N_2 in MAGNET facility (Q9 – Q12)

- Instrument air test article at UW and deliver to MAGNET facility for integration and test.



	Quarter (relative to start of project)											
	1	2	3	4	5	6	7	8	9	10	11	12
Task 1: Develop micro-reactor model	▨	▨	▨	▨								
Task 2: Develop integration HX model	▨	▨	▨	▨	▨					▨	▨	▨
Task 3: Techno-economic optimization		▨	▨	▨	▨	▨						
Task 4: Procure test articles						▨	▨	▨				
Task 5: Demonstrate perf. w/sCO_2 at UW								▨	▨	▨	▨	▨
Task 6: Demonstrate perf. w/N_2 at MAGNET									▨	▨	▨	▨

Task 1: Develop Balance of System Models



Heat pipe

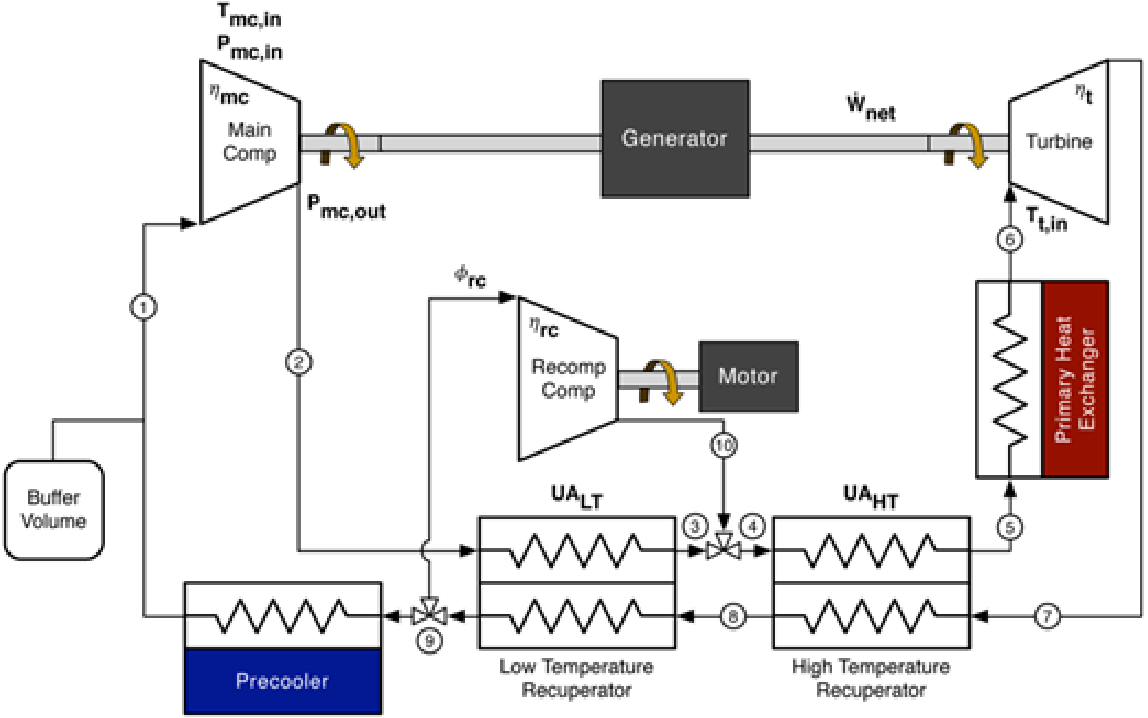
End-use cycle

Reactor core

Conceptual schematic of microreactor interfaced with air-Brayton cycle, from Abou-Jaoude et al., (2021) [1]

End-use cycle

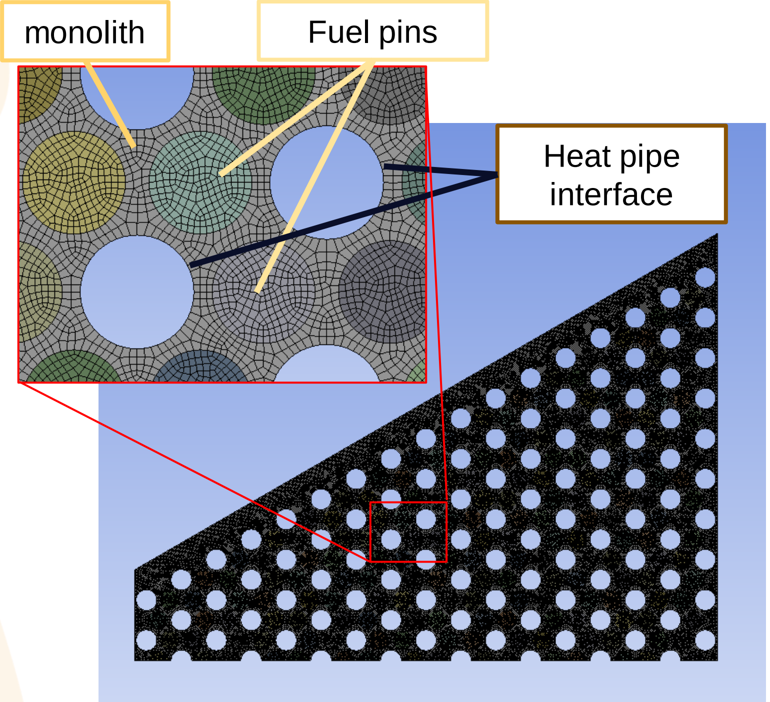
- Implemented in Engineering Equation Solver (EES) [2]
- Recompression sCO_2 cycle and recuperated air-Brayton cycle
- Integration heat exchanger performance included as pressure drop and approach temperature difference
- Still under development



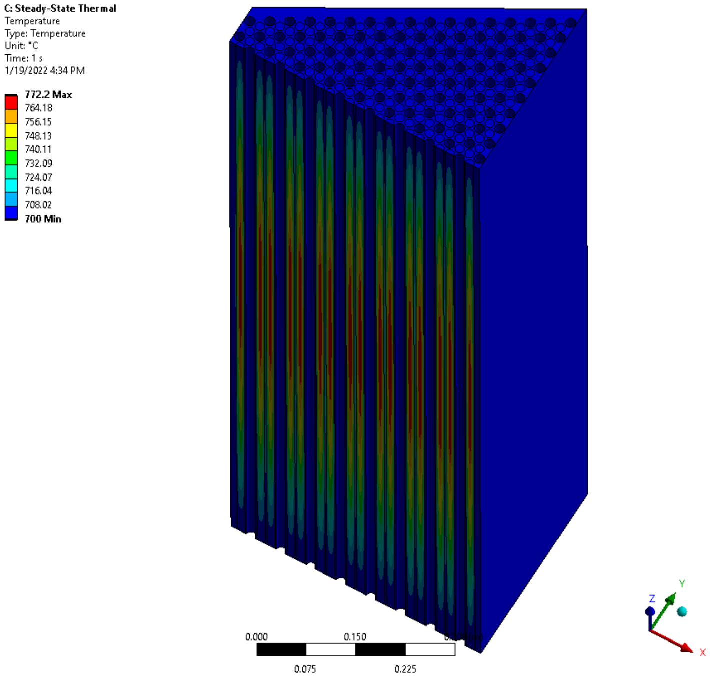
Schematic of recompression sCO_2 cycle, from Dyreby et al., (2014) [3]

Microreactor

- Developed 1/12th symmetry model of microreactor core in both MOOSE and ANSYS
- ANSYS model runs more quickly and provides the necessary information for this project
  - Thermal resistances from evaporator to fuel center
  - Interaction between fuel rods based on non-uniform evaporator temperature

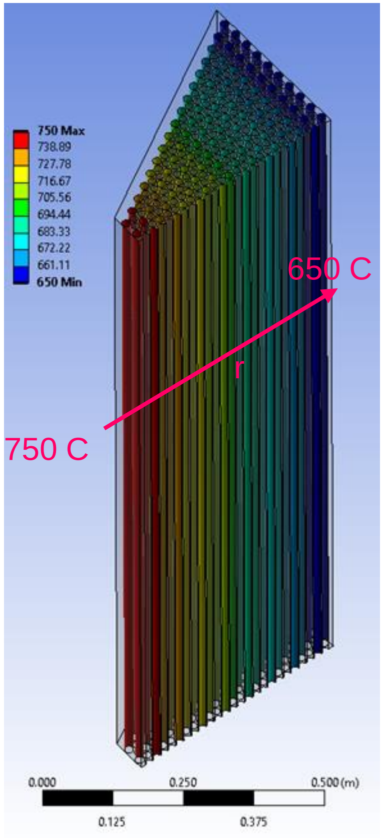


1/12th symmetry mesh of 316L stainless steel monolith and UO2 fuel pins (2D face swept into 150 sections over 1.5 m core height)

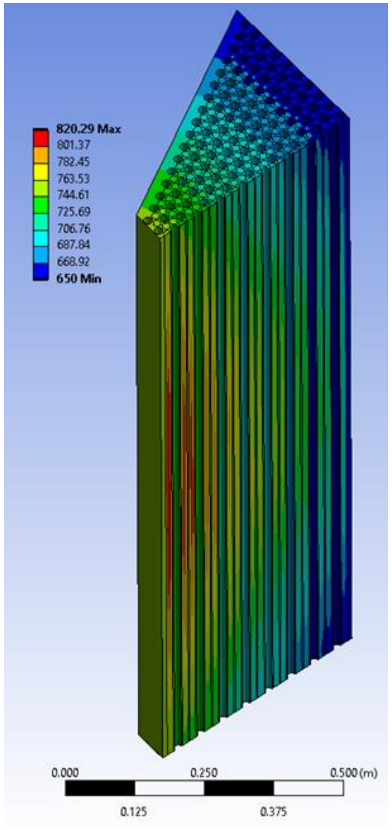


Fuel centerline temperatures peak 72.2 K above uniform 700°C Na heat pipe evaporators

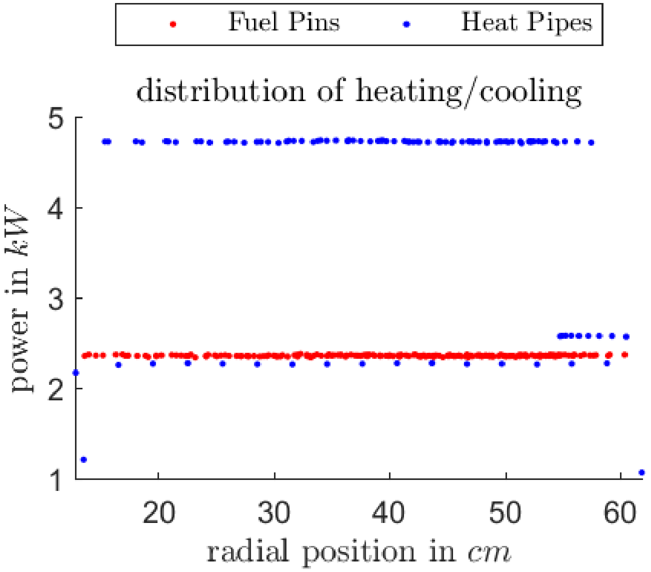
Microreactor: 5 MW removed by heat pipes



Heat pipe evaporator temperature decreases radially from 750 C to 650 C



Monolith and fuel temperatures under radially decreasing heat pipe temperature
(fuel centerline is max temp due to cosine power profile)



There is minimal interaction between heat pipes – even under conditions of radially varying evaporator temperatures all heat pipes provide similar rate of heat transfer.

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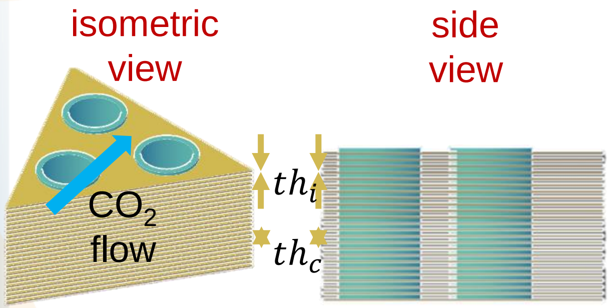
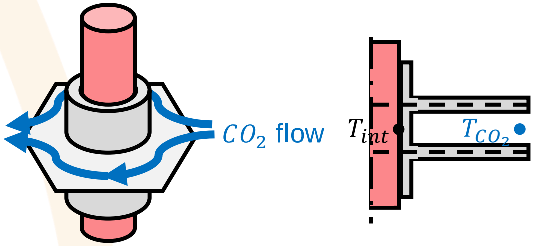
PCHE Integration Heat Exchanger

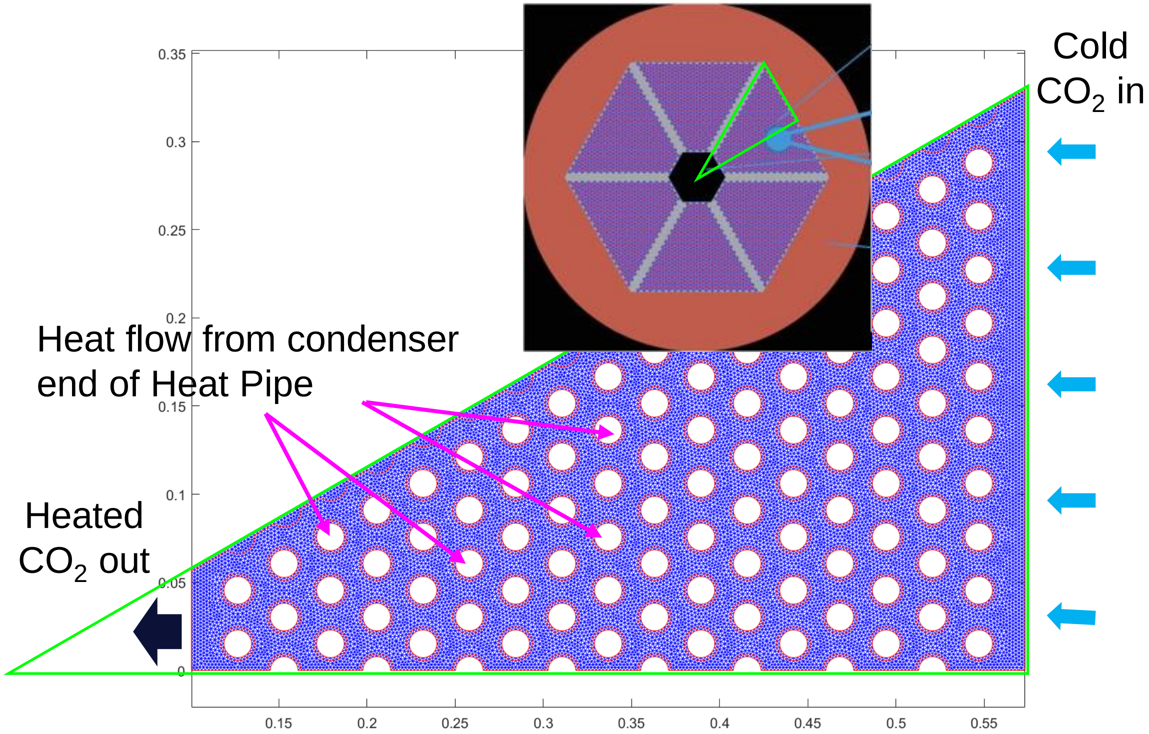
- Developed a component model of a cross-flow printed circuit heat exchanger where CO_2 coolant flows through micro-channels and around embedded heat pipes.
- Utilizing a homogenization approach to pressure drop and heat transfer within the micro-channels.
- Allows investigation into operating conditions, flow configuration, and temperature distribution.

Unit cell of heat pipe HX core





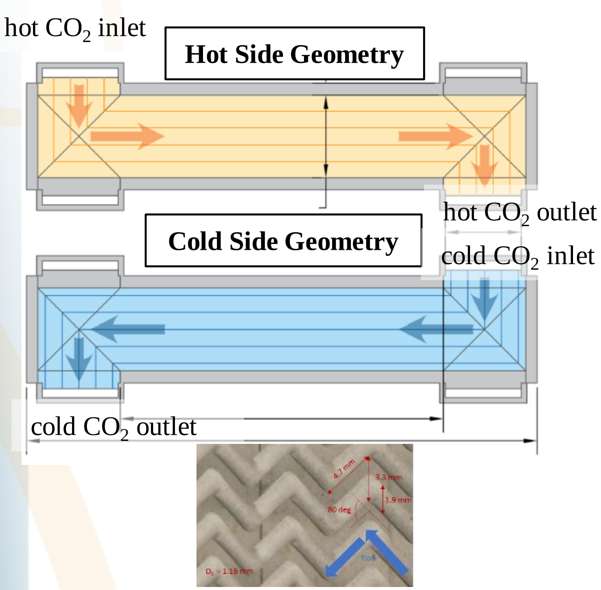
Micro-channel core behavior is described by volume fraction, friction factor, and heat transfer coefficient.



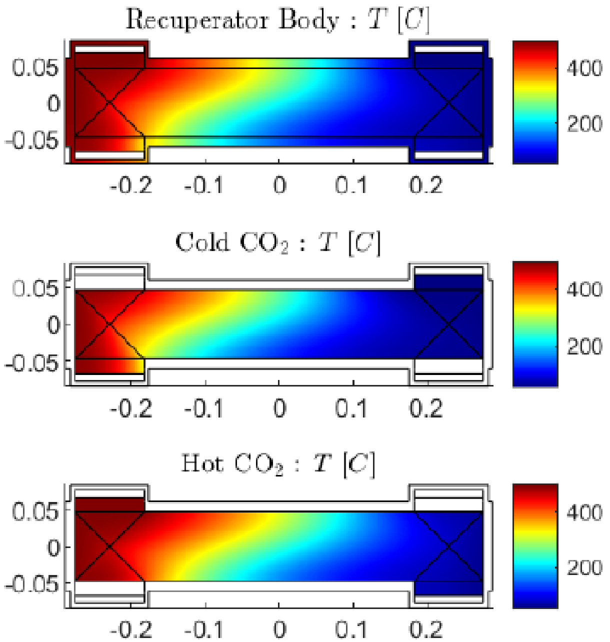
1/12th symmetry mesh of PCHE heat exchanger model. Holes are where heat pipe condensers interact.

PCHE Heat Exchanger Model

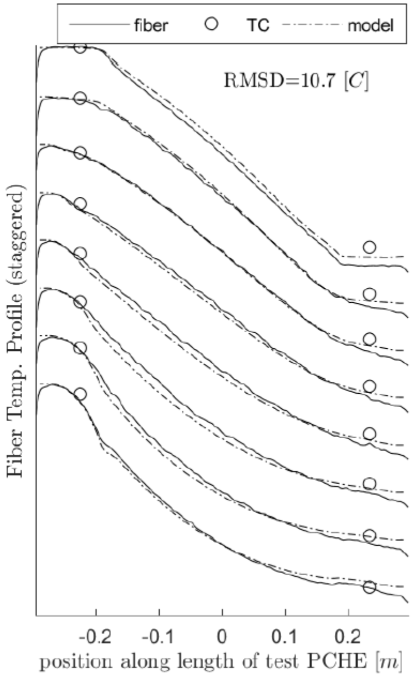
- Modeling technique has been proven for CO_2 recuperator applications through experimental comparison [7].
- Verified correlations for micro-channel pressure drop and heat transfer.
- Model predictions matched steady state experimental data over a large range of flow (1,000-64,000 Reynolds number).



Zig-zag channel PCHE flow layout and micro-channel geometry



Homogenized model results for PCHE recuperator Body, cold and hot stream CO_2, temperatures (at design flow 0.0336 kg/s , 5,131-6,097 *Re)*



Comparison of PCHE internal temperatures as predicted by model and measured using fiber-optic and TC probes (at design flow 0.0336 kg/s , 5,131-6,097 *Re)*

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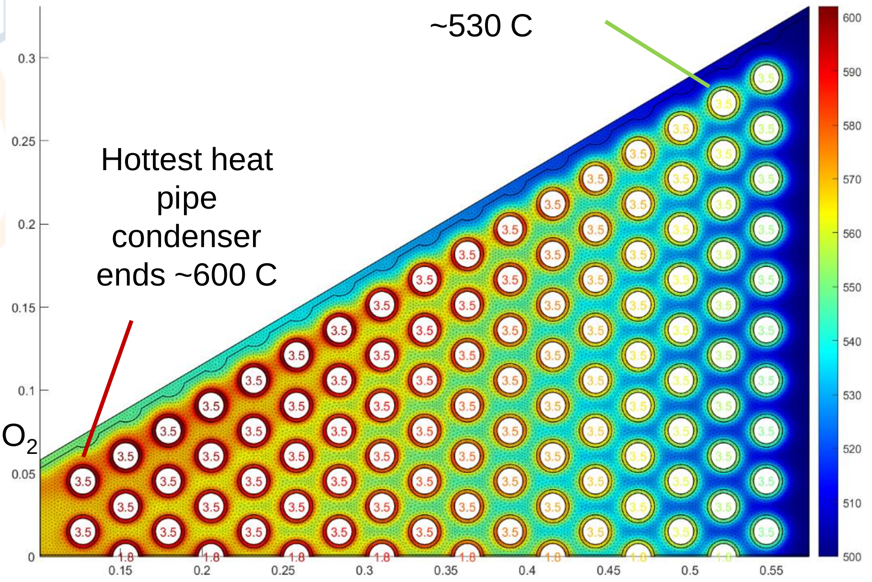
PCHE Integration Heat Exchanger

- Preliminary results for open channel design.



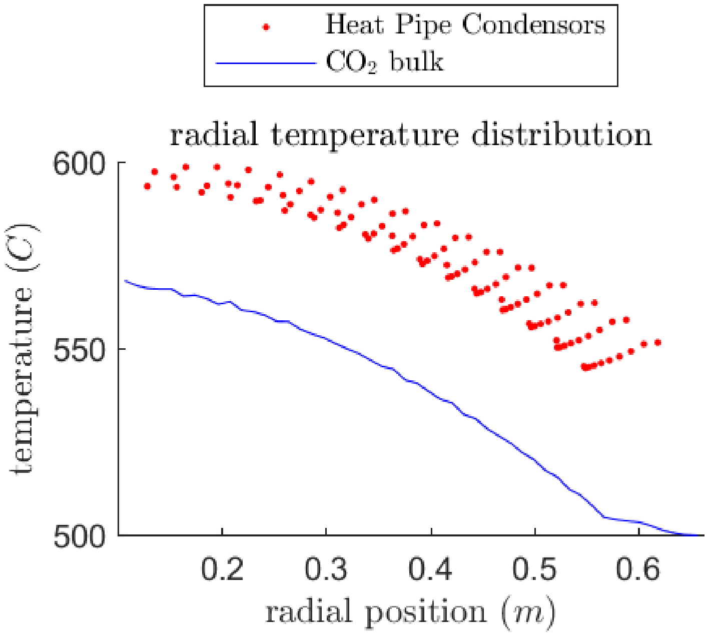
coolest heat pipe condenser ends ~530 C

Hottest heat pipe condenser ends ~600 C

Heated CO_2 out

Cold CO_2 in

Distribution of heat exchanger and heat pipe interface temperature at 5 MW of reactor input and 60 kg/s of CO_2 coolant flow.



CO_2 bulk and condenser temperatures as a function of radial position

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Progress Towards Milestones for Year 1

Milestone 1: Development of Balance of System Models

- Due: 9/30/22
- Deliverable: Technical report
- Progress: Cycle model are 50% done. Heat pipe model complete and integrated with EES. Microreactor model complete and efforts are underway to develop surrogate model suitable for integration with EES.

Milestone 2: PCHE Integration Heat Exchanger Model Complete

- Due: 6/30/22
- Deliverable: Technical report
- Progress: Modeling tool complete but not integrated with balance of system components. Modeling tool needs to be integrated with optimizer to allow design studies.

Milestone 3: Baseline PCHE Design Complete

- Due: 3/31/23
- Deliverable: Technical report
- Progress: Will begin once all modeling tools are available.

Future Work and Conclusions

Short term:

- Complete development of modeling tools and integrate.
- Develop design methodology.
- Complete initial design of sCO_2 and air heat exchangers.
- Pass relevant data on to INL for technoeconomic assessment.

Longer term:

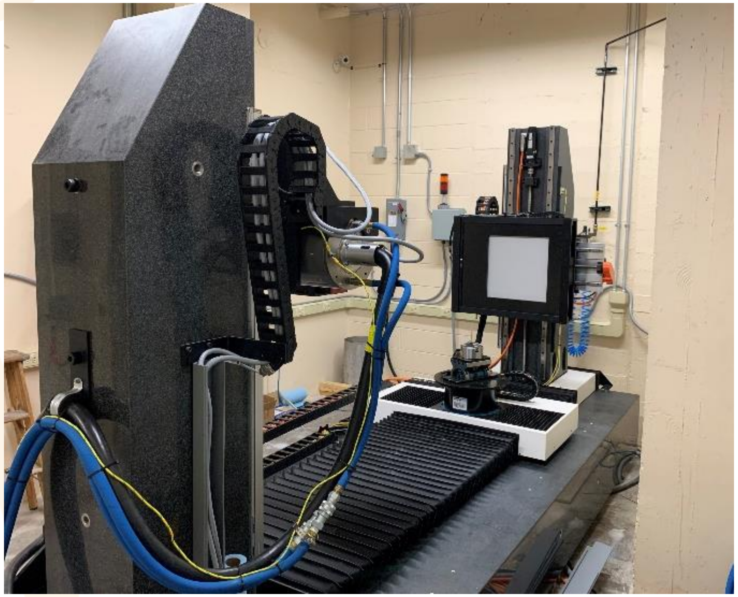
- Complete technoeconomic analysis.
- Develop sub-scale designs and procure test articles.
- Instrument and install test articles in sCO_2 loop (UW) and MAGNET (INL).

Open questions:

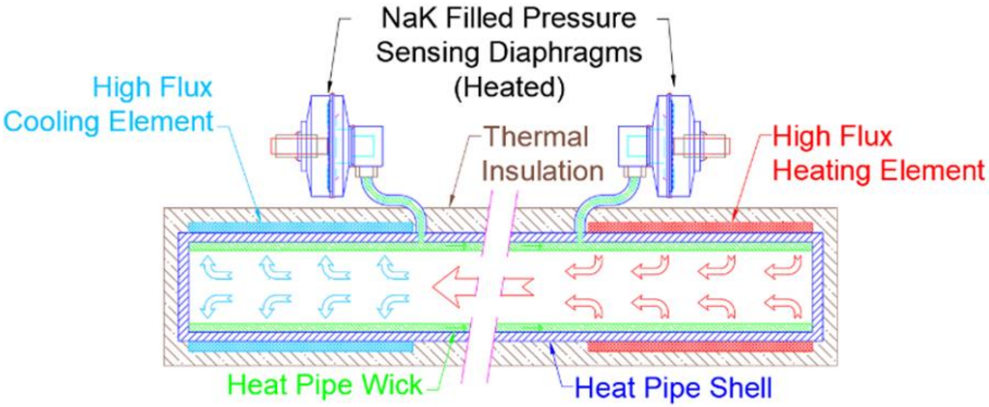
- Heat pipe to heat exchanger interface. High conductivity bonding/joining processes.
- Access to heat pipe codes .
  - SockEye
  - New version of HTPIPE, we have tested an older version (Prenger, 1979 [5])

Planned Heat Pipe Testing

- Measurement of heat pipe temperature profile in both steady-state and transient start-up operation.
- Use FO-DTS sensors for high-resolution measurements of internal temperature distribution.
- Measurement of heat pipe pressure profile will be challenging and will require Na-filled pressure transducers.
- Imaging of heat pipe in operation using 450 kV X-ray facility.



450 kV X-ray CT scanner



Schematic of pressure transducer measurement

References

[1] Abou-Jaoude, A., A. Foss, Y. Arafat, and B. Dixon, *An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept*, INL/EXT-21-63067 (2021).

[2] Klein, S.A., *EES – Engineering Equation Solver*, Version 11.303, F-Chart Software, https://fchartsoftware.com

[3] Dyreby, J., S. Klein, G. Nellis, and D. Reindl, "Design Considerations for Supercritical Carbon Dioxide Brayton Cycles with Recompression," *J. of Eng. For Gas Turbines and Power*, Vol. 136(10), (2014).

[4] Prenger, F.C., *Heat Pipe Computer Program (HTPIPE), User's Manual*, LA-8101-M, November (1979).

[5] Matthews, C., B. Wilkerson, R. Johns, H. Trellue, and R.C. Martineau, *Task 1: Evaluation of M&S tools for micro-reactor concepts*, LA-UR-19-22263, (2019).

[6] Morton, T.J., *Integrated Energy Systems Development*, INL/MIS-20-59847D, Sep. (2020).

[7] Jentz, I. and M. H. Anderson, *"Coupled Heat Transfer and Hydraulic Modeling of an Experimental Printed Circuit Heat Exchanger Using Finite Element Methods," Journal of Thermal Science and Engineering Applications*, Vol. 13(3), 2021.

[8] Chi, S. W.. *Heat pipe theory and practice: A sourcebook.* Hemisphere Publishing Corporation, Washington, D. C., (1976).

[9] Teng, W., X. Wang, X., and Y. Zhu, "Experimental investigations on start-up and thermal performance of sodium heat pipe under swing conditions," *Int. J. of Heat and Mass Transfer*, Vol. 152, (2020).

Questions

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