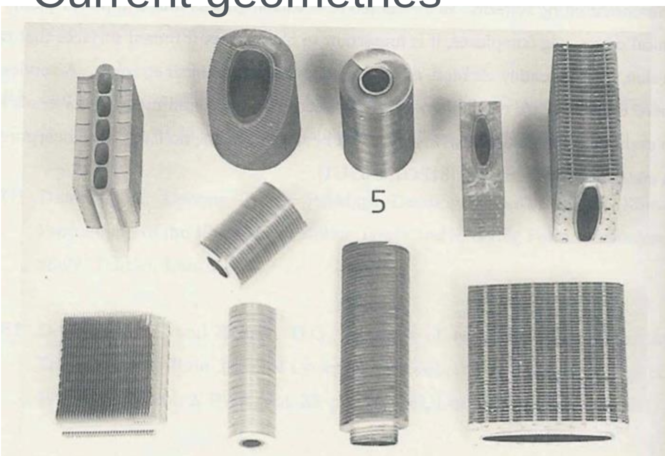
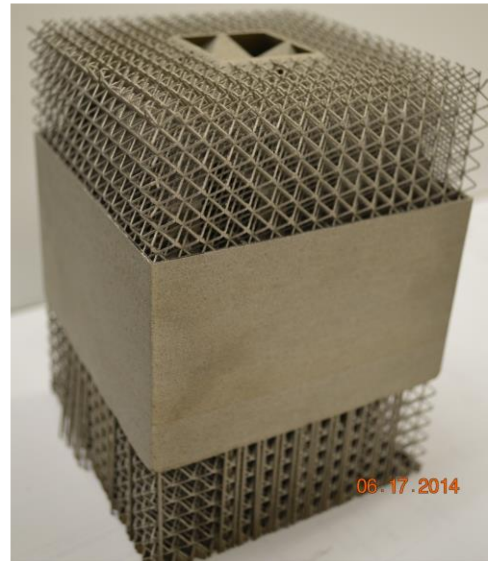
Current geometries




Proposed geometries




**Sabau A.S., Klett J., Dehoff R., Bejan A. (Duke U.),**
**Jones J., Nejad A. (UTK), Polsky Y., Gruszkiewicz M., and Mines G. (INL)**

# Freeform Heat Exchangers for Binary Geothermal Power Plants

Project Officer: Tim Reinhardt

Total Project Funding: $190K and $280K (FY14, FY15)

May 12, 2015

**Adrian S. Sabau**
**Oak Ridge National Laboratory**

Low Temperature

# Relevance/Impact of Research

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- **Objective:** Develop compact & efficient heat exchangers for geothermal power plants, tailored for specific working fluids.
- **Challenges and barriers addressed:** Significant difficulties in reducing the cost of electricity for ORC binary power plants operating with brine at less than 150°C
- **Impact on cost, performance, applications, and markets**
  - Attaining an overall heat transfer coefficient for the new heat exchanger of 140 $W/m^2K$ at the same cost (2X compared with current baseline).
  - The decrease in the footprint and associated costs of heat exchangers would lower the geothermal LCOE.
- **Impact to GTO goals**
  - Goal 9 – developing low-cost, high-efficiency energy conversion technologies for EGS
  - Barrier N (Energy conversion at low temperature)
  - 3 GWe of installed low-temperature geothermal capacity by 2020
- **Innovative aspects of the project**
  - Involve novel fabrication routes, such as Additive Manufacturing, for creating novel near-net shape structures,
  - New designs would have optimum (and different) geometry features according in different regions (liquid-to-liquid, two-phase-to-liquid, and gas-to-liquid),
  - Assess the use of carbon-foam for geothermal heat exchangers.

# Scientific/Technical Approach

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| *Task* | *Description* |
|---|---|
| 1) Assess the applicability of AM and carbon foam for heat exchangers used in geothermal industry. | The material and fabrication costs will also be obtained. |
| 2) Propose novel geometry for heat transfer passages and overall heat exchanger architectures. | The envisioned evaporator designs include three sections, each with its own geometry features, according to the working fluid state: liquid-to-liquid, two-phase-to-liquid, and gas-to-liquid. |
| 3) Conduct Computational Fluid Dynamics (CFD). | To assess the performance of heat exchangers, friction factors (pumping power), thermal resistance (heat transfer coefficients, or Nusselt number), Colburn j factor |
| 4) Fabricate small heat exchanger components using AM and/or carbon foam facilities at ORNL. | Small scale prototypes will be fabricated to establish the proof of principle for the fabrication of compact heat exchanger components. |
| 5) Fabricate test loop for geothermal-relevant conditions. | Design and built a test loop that will enable the testing of heat exchangers (1-5kW) under conditions and refrigerants relevant geothermal power plants. |
| 6) Test prototype components | R134a and R245fa refrigerants will be used in tests. |

# Scientific/Technical Approach: Specific technical challenges

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| ***Key Issues*** | ***Challenge*** |
|---|---|
| *Design new geometries & architectures* | Design space too large |
| *Additive Manufacturing applicability* | How to apply to large components? |
| *Two-phase CFD* | Accurate simulations |
| *Prototype heat exchanger* | Fabricate 1-10 kW heat exchanger |
| *Carbon foam* | Corrosion with Al and steel |
| ORC | Refrigerant selection |
| Two-phase flows | How to lower pressure drop? |
| Brine flow | Silica precipitation |

# Scientific/Technical Approach

| ***Item/Feature*** | ***Proposed Approach*** |
|---|---|
| *Design new geometries & architectures* | 1. Identifying optimum non-circular cross-sections based on scale analysis and CFD simulations<br>2. Use constructal theory for systematic multi-scale design<br>3. Use multi-scale design: developing flow in smallest level |
| *Additive Manufacturing* | 1. Fabricate entire small heat exchangers (1-10kW heat load).<br>2. Fabricate manifolds and other intricate-shape sub-components for large HX. |
| *Two-phase CFD* | Work with CD-Adapco, Inc. to implement accurate thermophysical properties |
| *Baseline heat exchanger* | Work with ElectraTherm, Inc. to identify a 1-10kW baseline heat exchanger. |
| Efficiency of binary power plants | Supercritical two-phase (R134a) and ORC (R245fa) |

# Accomplishments, Results and Progress

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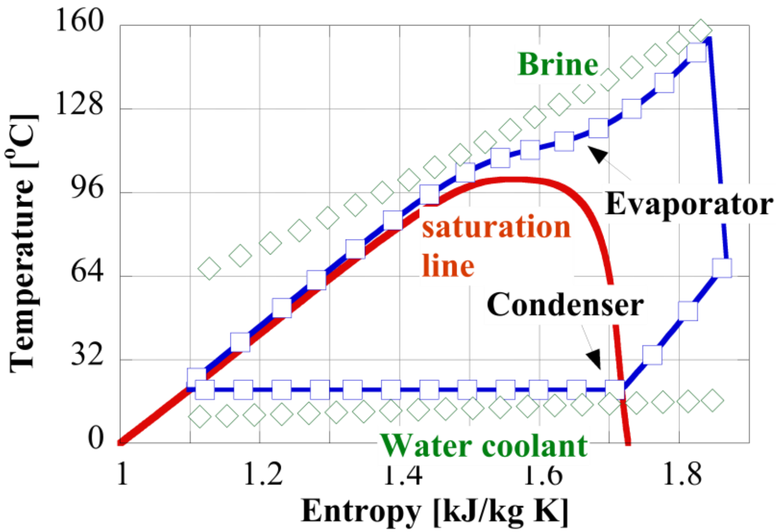
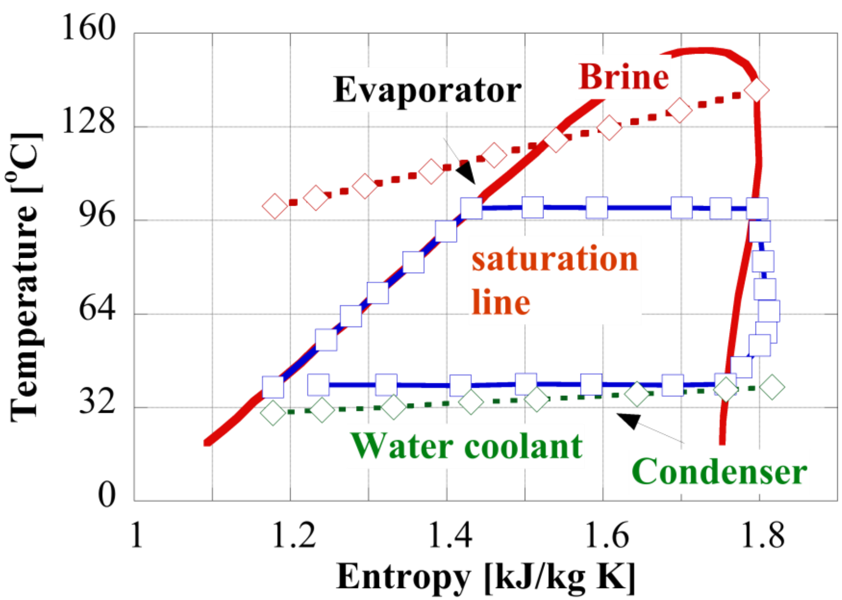
| Type | Original Planned Milestone (OPM), or Technical Accomplishment (TA) | Actual Milestone/Technical Accomplishment | Date Completed |
|---|---|---|---|
| TA | Working fluid selection | R134a - Supercritical two-phase<br>R245fa – for typical ORC | 11/1/2014 |
| TA | Proof-of-principle of using Additive Manufacturing (AM) to fabricate new heat exchanger architectures. | Fabricate a new heat exchanger based on a bifurcating flow concept. | 6/10/2014 |
| TA | CFD on sub-model heat exchanger | Preliminary data for carbon-foam Ti heat exchangers | 8/18/2014 |
| OPM | Identify two new multi-scale architectures for the evaporator, including geometries for internal passages | 1. Identified staggered triangular-pipe flow<br>2. Square flow cross-section more performant than circular cross-section flow | 2/31/2015 |
| TA | Identify new flow path geometries | Investigate triangular and square cross-section pipes | ongoing |

# Accomplishments, Results and Progress: Identify two refrigerants

| Refrigerant | Cycle | Advantage | Disadvantage |
|---|---|---|---|
| R134a | Supercritical two-phase | High brine effectiveness | High pressure, more expensive to test |
| R245fa | Rankine subcritical | Lower pressure, easier to test than R134a | Lower brine effectiveness |



# Accomplishments, Results and Progress: bifurcating cell enabled a low pressure drop within the two-phase region

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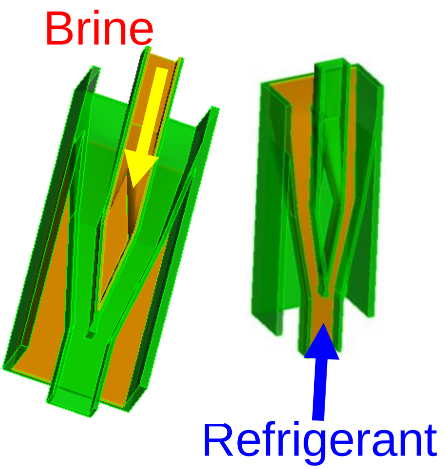


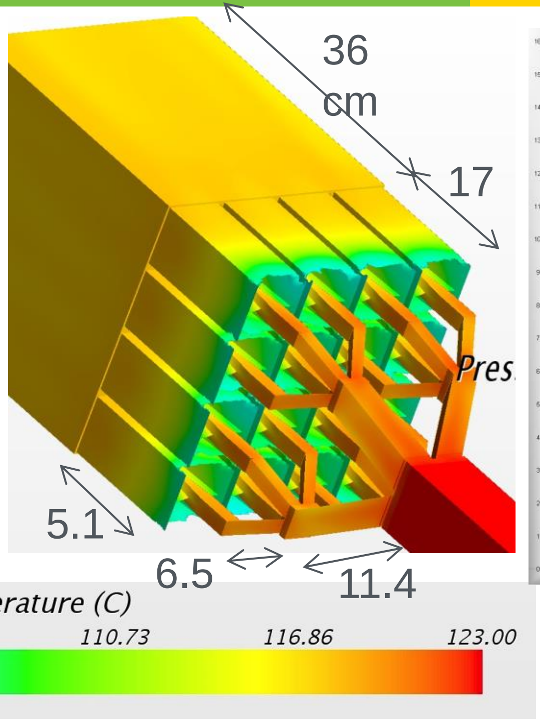


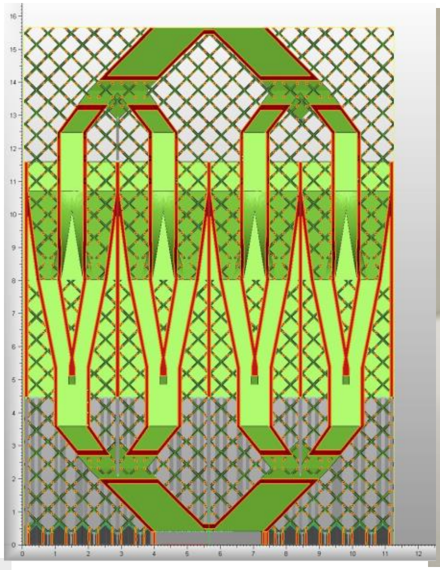

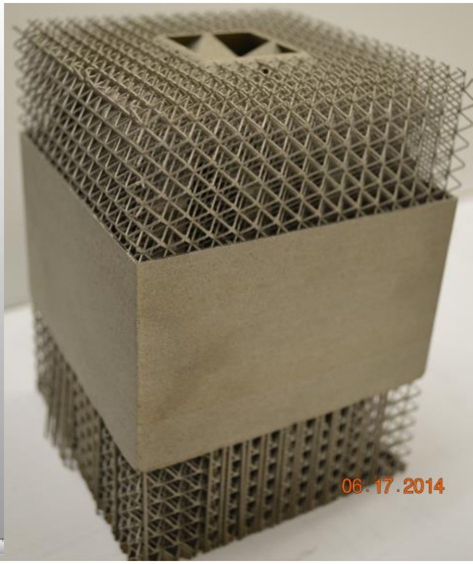


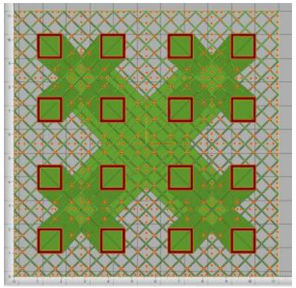

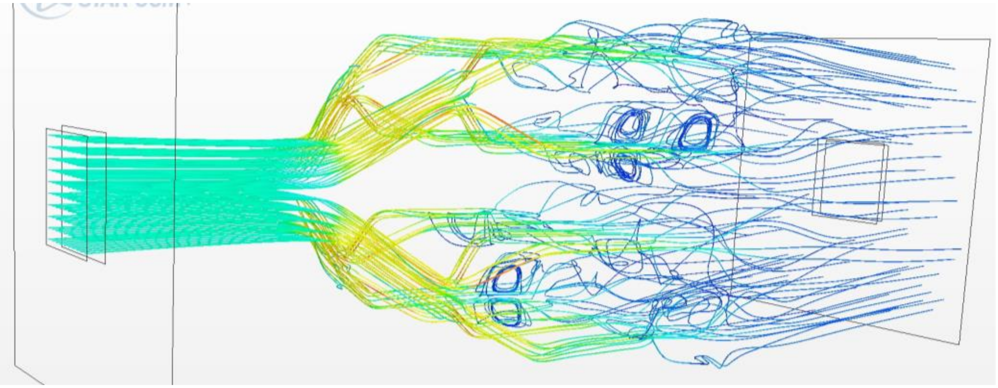

The CFD analysis revealed needed areas of improvement such as reducing/eliminating recirculating cells and stagnation areas.

# Accomplishments, Results and Progress: Preliminary data for carbon-foam Ti heat exchangers

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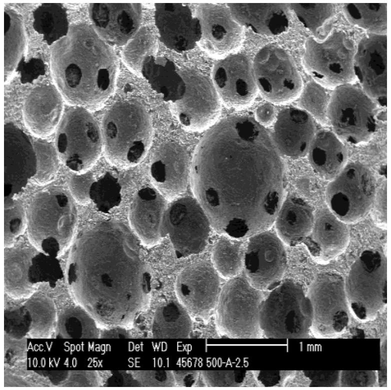
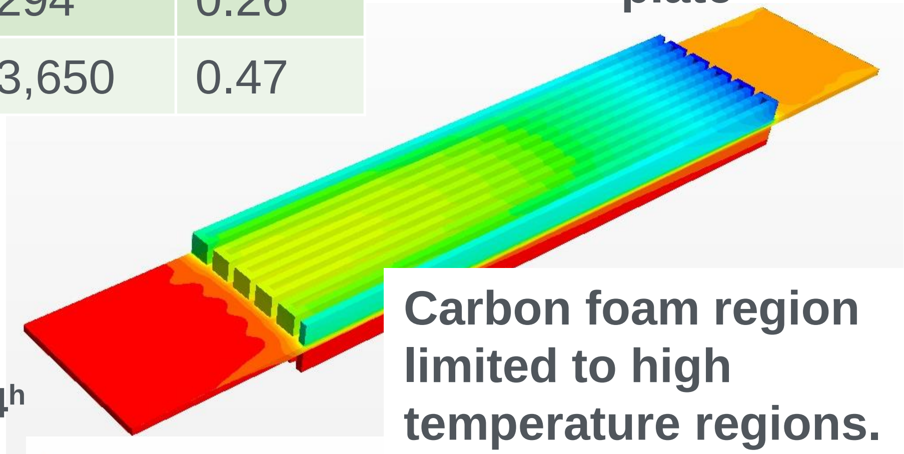
| Configuratio n | $Q_h$ [W] | UA [W/K] | A [$m^2$] | HX Eff | U [$W/m^2.K$] | NTU |
|---|---|---|---|---|---|---|
| Bifurcating* | 1,425 | 46 | 0.25 | 73.5 | 294 | 0.26 |
| CF-Ti (plate) | 1,841 | 64.9 | 0.018 | 0.336 | 3,650 | 0.47 |



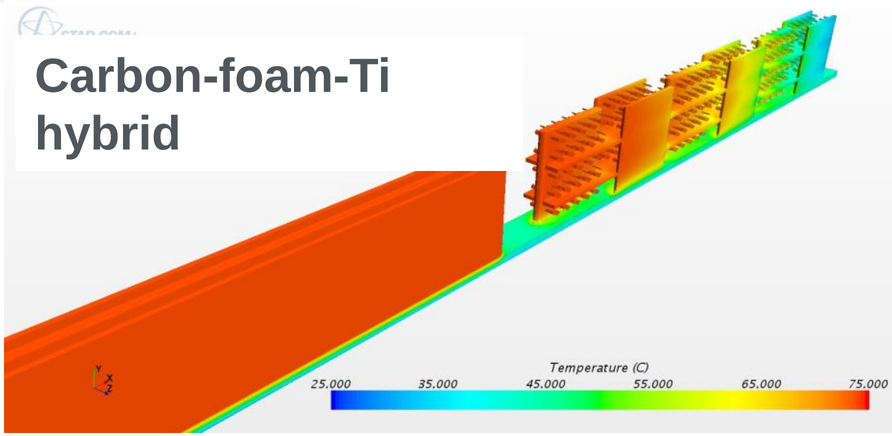
- Highly ordered graphitic ligaments:
  - Graphite-like properties
  - 30% more thermally conductive than Al, at 1/4th the weight
  - λ approx. 240 W/mK

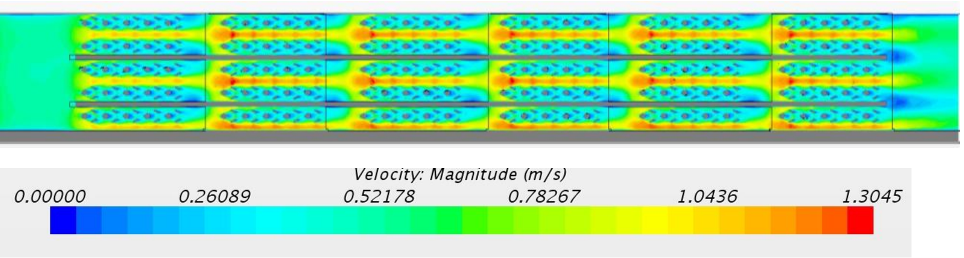
**Carbon-foam-Ti plate**



**Carbon foam region limited to high temperature regions.**

**Carbon-foam-Ti hybrid**



# Accomplishments, Results and Progress: A heat exchanger was developed based on triangular-cross-section pipes

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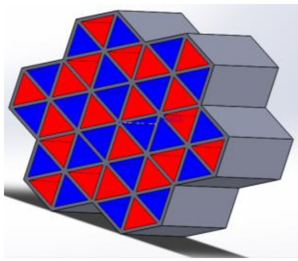
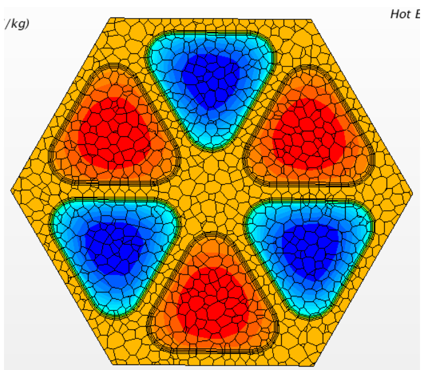




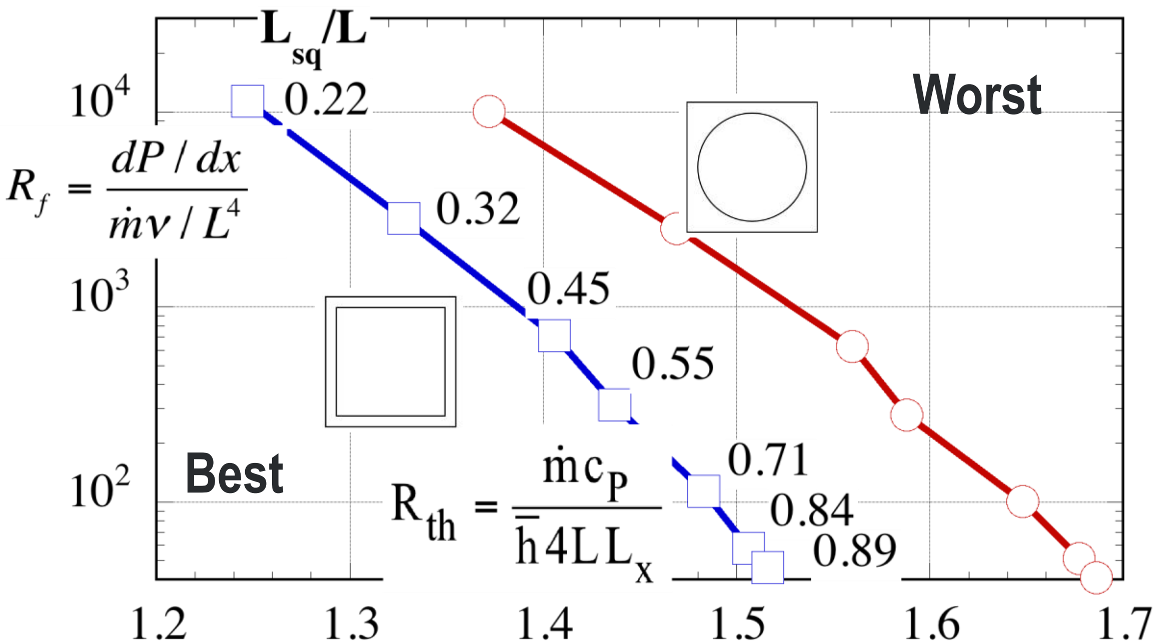

Staggered arrangement of brine/refrigerant flows increases the heat exchanger effectiveness.

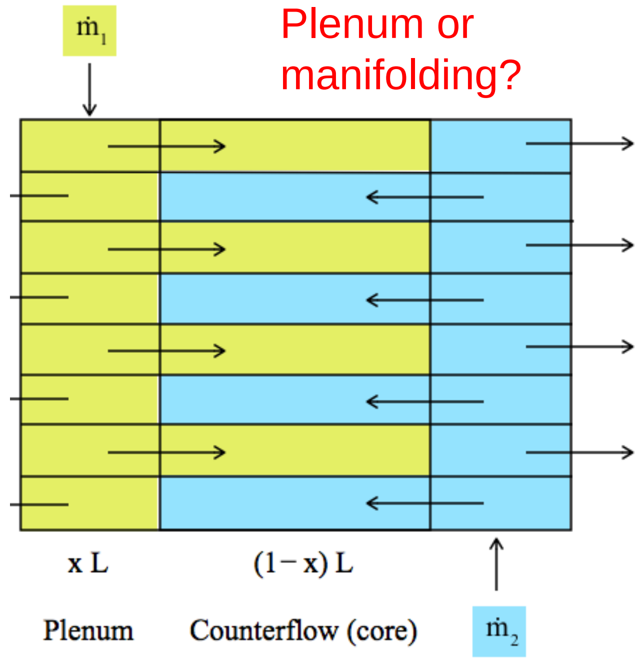

Triangular-cross-sectional pipes, arranged in an hexagonal packing, allowing for:

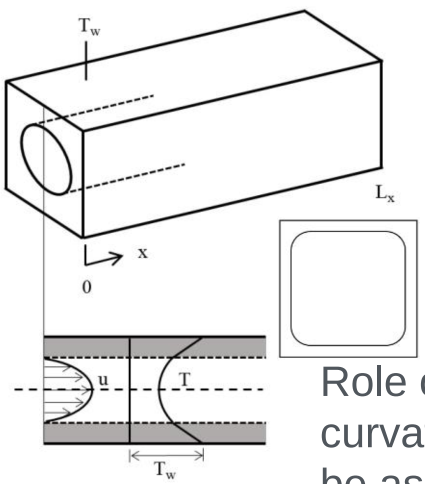
- large surface area for heat exchange,
- smallest thermal resistance due to thin walls between the two flow streams, and
- minimal metal use.

# Accomplishments, Results and Progress: Investigate non-circular cross-sections (Duke U.)



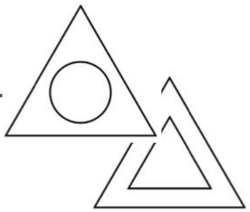


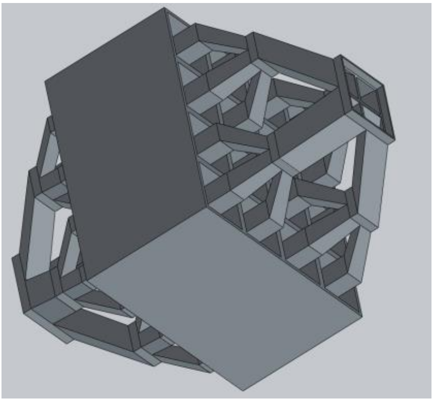




CFD simulations and scale analysis conducted at Duke University (prof. Bejan) indicate that pipes of square cross-sections, which are embedded in the solid, would be more efficient than circular pipes.

Role of corner curvature will be assessed.



CFD simulations and scale analysis will be conducted at Duke University (prof. Bejan) for triangular cross-sections.



# Accomplishments, Results and Progress: Automatic generation of heat exchangers architectures

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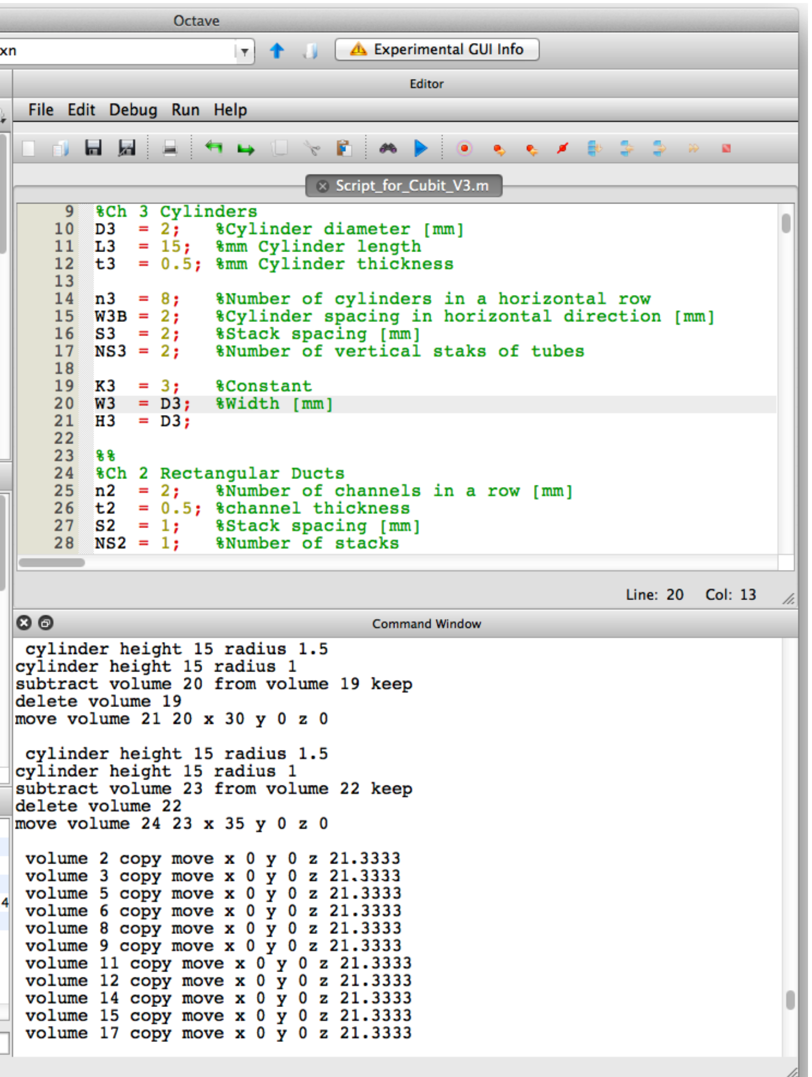
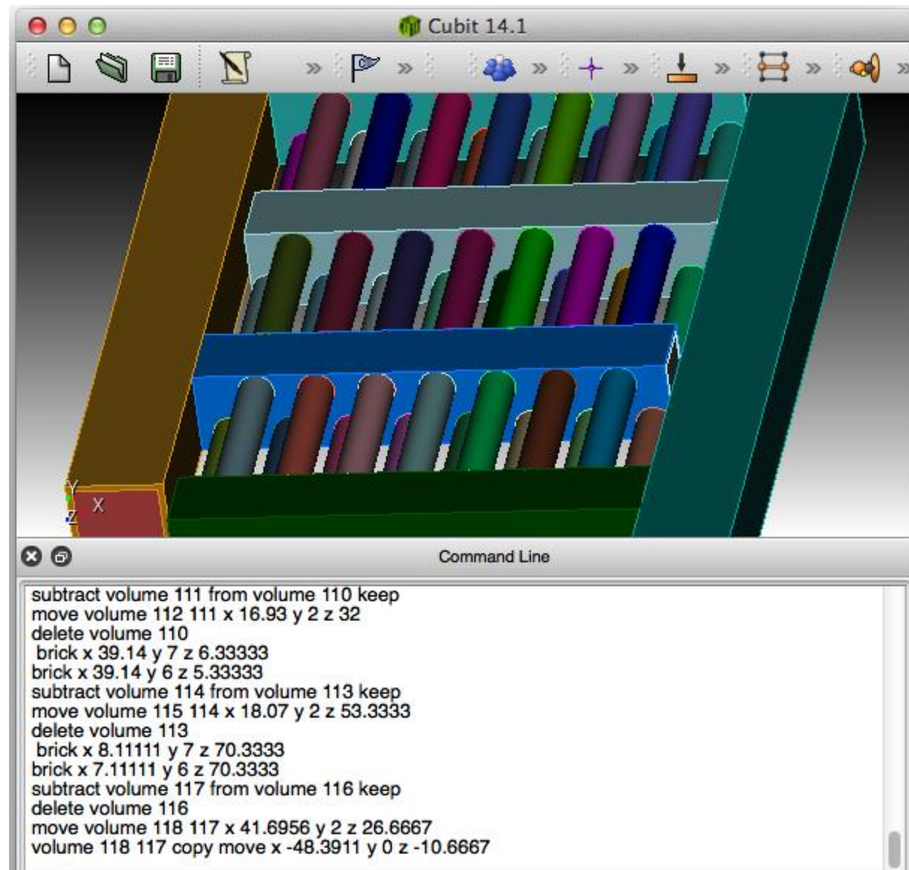



Automatic generation of HX CAD and performance:

1. Excel spreadsheet for evaluating laminar flow performance, and
2. Matlab code for automatically generating CAD data.
3. Automatic generation of CAD files in Cubit.



# Accomplishments, Results and Progress: Automatic generation of heat exchangers architectures

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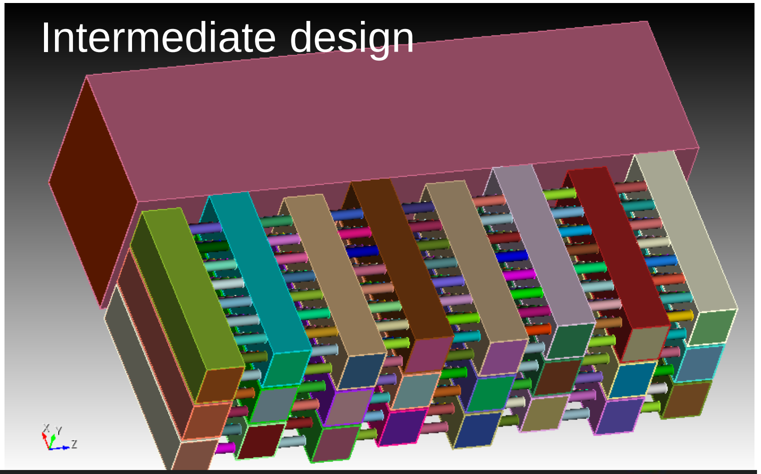
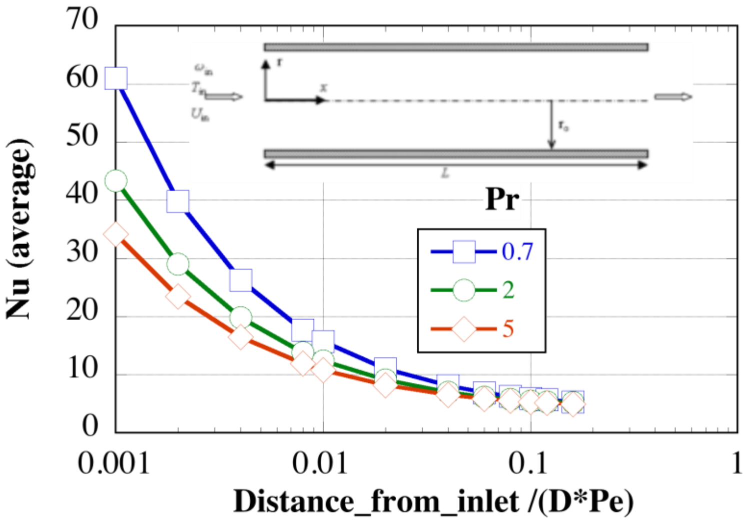
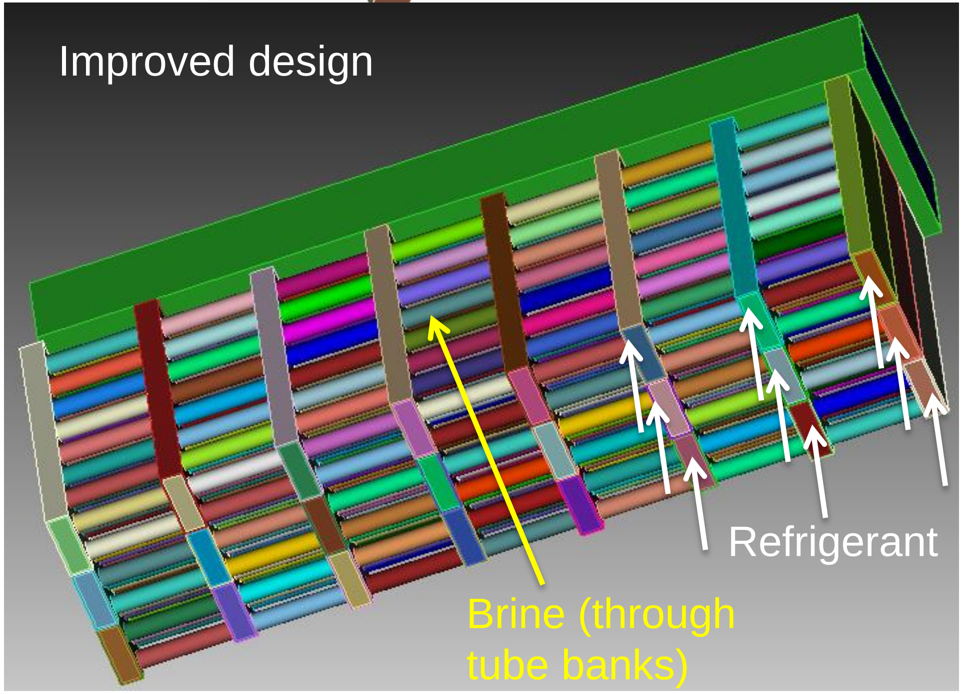
Optimization criteria identified:
1. Surface area per unit volume
2. Mass of alloy
3. Pressure drop
4. U*A

Examples of tri-scale HX design (inlet plenum removed for clarity) by employing developing flow at smallest level




Enhanced heat transfer in the entrance region.



# Future Directions

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| Milestone or Go/No-Go | Status & Expected Completion Date |
|---|---|
| Subcomponent fabrication/Complete the fabrication of two subcomponents using AM | On schedule for 6/30/2015 |
| Complete building of test loop | On schedule for 7/15/2015 |
| **Evaporator heat exchanger design | *9/30/2015 |
| Demonstrate experimentally an increase of 100% in the overall heat transfer coefficient of the new heat exchanger as compared to the current baseline of 70 $W/m^2K$ at the same cost. | 9/30/2016 |

** Go/No-Go 2015 decision criteria: Independent confirmation that new design can be experimentally compared to conventional design to compare overall heat transfer coefficient
***Go/No-Go 2015 description: Complete a detailed design of an AM/carbon foam evaporator that can be compared to a conventional shell and tube or plate heat exchanger used in geothermal applications. Heat exchangers will be scaled down versions (1-5 kW).

**Deployment**:

- Provide technical data on heat exchangers to ElectraTherm Inc. and Koppers Inc. to identify pathways for deployment.
- Identify other collaborators from industry.

# Future Directions: Remaining technical challenges

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| *Remaining technical challenges* | *Pathways to overcame remaining technical challenges* |
| --- | --- |
| *Design space too large for new geometries & architectures* | • Work with industrial partners to identify areas of development<br>• Systematic design based on optimization criteria<br>• Automatic generation of evaporator design |
| *Prototype heat exchanger* | Fabricate 1-10 kW heat exchanger |
| *Silica precipitation* | • Identify regions in the evaporator prone to silica precipitation near the brine exit area,<br>• Formulate geometry requirements to minimize silica precipitation<br>• Identify flow rate effect on silica precipitation |
| *Cost* | Consider fabrication and materials cost at the design phase |

# Mandatory Summary Slide

- Additive manufacturing can be used to fabricate:
  - small evaporators for customized applications manifolds, and
  - intricate-shape sub-components for large evaporators
- Carbon foam has limited use for the evaporator in binary geothermal plants due to the combined cost of the foam and Ti,
- Management of silica precipitation is difficult to consider at the design phase,
- A systematic approach for evaporator design, involving carefully selected optimization criteria, was developed,
- Targeted CFD modeling of sub-scale features are important,
- Performance evaluation using existent correlations for laminar (and turbulent flow, if available) is crucial for HX design screening in the early stages of development.