Geometry Design and Transient Simulation of a Heat Pipe Micro Reactor
Dr. Jun Wang
University of Wisconsin - Madison, USA
18 November 2021
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Meet the Presenter

Dr. Jun Wang is an associate scientist of Nuclear Engineering and Engineering Physics at the University of Wisconsin-Madison. His research interests include the advanced numerical analysis of nuclear safety and reliability for various reactor designs. He is leading a few projects on the heat pipe micro reactor, high temperature gas cooled reactor transient analysis, and uncertainty quantification by artificial intelligence. He is also serving on the ANS thermal hydraulics committee, and the journal Progress in Nuclear Energy, Annals of Energy Research as editorial board.

Dr. Wang earned his Ph.D. from Xi’an Jiaotong University.

Email: jwang564@wisc.edu
Content

• MICRO REACTOR REVIEW

• NUMERICAL TOOL AND BENCHMARK

• STEADY STATE AND SENSITIVITY ANALYSIS

• TRANSIENT SAFETY SIMULATION

• CONCLUSION
Microreactor Development

- Micro-reactors are of interest due to flexible, reliable;
- Small, transportable, on-site installation;
- Support deep space, government off-grid, remote communities, e.g.,

- Designs include heat pipe cooled and gas cooled micro-reactors;
- Research demonstrate designs are safe, and efficient.

Heat Pipe Microreactor Research
Past work for Heat Pipe Micro-Rx’s

• Heat pipe cooling technology has been widely applied since 1960s for specialized applications
• Space exploration projects: KRUSTY, HOMER, SAIRS, HP-STMCs, MSR, etc.

*NASA and National Nuclear Security Administration engineers lower the wall of a vacuum chamber around the Kilo power reactor system
## Industrial effects

<table>
<thead>
<tr>
<th>Project</th>
<th>Company</th>
<th>Fuel</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Pipe Cooled Microreactor</td>
<td>eVinci</td>
<td>Westinghouse</td>
<td>UO$_2$ or TRISO*</td>
</tr>
<tr>
<td></td>
<td>Aurora</td>
<td>Oklo</td>
<td>Metallic Uranium-Zirconium</td>
</tr>
<tr>
<td>Gas-cooled Microreactor</td>
<td>Holos Quad</td>
<td>HolosGen</td>
<td>TRISO</td>
</tr>
<tr>
<td></td>
<td>Micro Modular Reactor</td>
<td>USNC</td>
<td>Fully Ceramic Microencapsulated</td>
</tr>
<tr>
<td></td>
<td>Xe-Mobile</td>
<td>X-Energy</td>
<td>TRISO</td>
</tr>
</tbody>
</table>

*TRISO: Tri-structural ISOtropic particle fuel
• Westinghouse’s eVinci design uses mature heat pipe technology developed by LANL
  – Comprised of solid block with 3 types of channels for fuel rods, moderators, heat pipes

• Oklo’s Aurora Powerhouse is inspired by NASA’s Kilopower reactor
  – Uses metallic uranium fuel alloy in a solid block with heat pipe cooling technology
Heat Pipe Flowchart

Heat Pipe is made of Wall, Wick, and Coolant

- In the evaporator, liquid coolant turns to vapor
- Vapor coolant goes through adiabatic region
- In the condenser, vapor coolant is cooled back to liquid
- Liquid coolant flows back through Wick

*Conventional HP:
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MOOSE can conduct multi-scale simulation (e.g., heat conduction)
- Plug-in infrastructure simplifies the definition of key physical processes, material properties, post-processing
SAM has Heat Pipe model to describe fluid flow and heat transfer behavior; assumes high rate of axial conduction in heat pipe and neglects vapor flow
Processes considered: Heat conduction, liquid flow/heat transfer, interfacial mass/momentum/energy transfer
• To verify SAM/MOOSE coupling, code-to-code comparison is first tested
• Geometry is a solid monolith block; 1 heater rod and 6 heat pipes (Na) – similar to ANL benchmark calculation
ANL Benchmark Comparison

- Time step for both cases is kept the same and results differ early in time
- Initial temperature set at 875K and solid monolith surfaces is adiabatic
- Heat pipe condenser temperature is 750K
- Heat produced in heater rod and removed by heat pipes

### Material Properties of HP Micro-reactor

<table>
<thead>
<tr>
<th></th>
<th>Monolith</th>
<th>Fuel Rod</th>
<th>Heat Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m⁻³)</td>
<td>1873.9</td>
<td>11,000</td>
<td>Vapor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wick</td>
</tr>
<tr>
<td>Specific Heat (J/kg)</td>
<td>1603.5</td>
<td>939</td>
<td>Wall</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK⁻¹)</td>
<td>30</td>
<td>18</td>
<td>1E+06</td>
</tr>
</tbody>
</table>

- Heat Pipe Microreactor Research
• Small differences at 10000s between ANL & UW analysis

• Both benchmarks use different # of nodes (25459 for ANL, 51573 for our HEX20 elements)

• Results indicate our modeling strategy can be used to couple solid core heat conduction to Heat Pipe cooling. It could potentially be expanded to other research.
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• Micro-reactor Agile Non-nuclear Experimental Test-bed (MAGNET) at INL
• Goal is to provide a test bed that is broadly applicable to multiple microreactor concepts (initial HP cooled configuration)

*Vacuum Chamber showing door and test article inside

Solid monolith with 54 fuels and 37 HPs
MAGNET Simulation

- MAGNET hexagonal solid monolith has: 54 heater rods and 37 heat pipes
- Fission heat is simulated with electric heater rods
- Monolith block and heat rods made up of stainless steel (SS 316L)
- Power distributions of heater rods are not finalized; assumed a \textit{cosine power shape} to approximate actual power profile
- Note: Temp. of monolith heaters (3D) and heat pipes (2D) calculated separately (MOOSE: monolith + rods, SAM: heat pipes)
MAGNET Simulation

- Heat generated transferred from rods to monolith and to embedded heat pipes
- Monolith temperature indicates that heater rods close to center have higher temp than outside edges
**GEN IV International Forum**  
**MAGNET Heat Pipe Model**

### Components:

#### Monolithic Block
- **Height:** 1 m
- **Diameter:** 0.244 m
- **Material:** SS 316L
- **Boundary Condition:** Adiabatic radial & axial

#### Electric Heaters
- **Quantity:** 54
- **Diameter:** 0.014 m
- **Material:** SS 316L
- **Total Pwr:** 75 kW

### Heat Pipe

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
<td>37</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>0.0156 m</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Vapor</strong></td>
<td>Na</td>
</tr>
<tr>
<td><strong>Wick</strong></td>
<td>SS 316L</td>
</tr>
<tr>
<td><strong>Wall</strong></td>
<td>SS 316L</td>
</tr>
<tr>
<td><strong>Outer Radius</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Vapor</strong></td>
<td>0.0053 m</td>
</tr>
<tr>
<td><strong>Wick</strong></td>
<td>0.0066 m</td>
</tr>
<tr>
<td><strong>Wall</strong></td>
<td>0.0078 m</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Evap</strong></td>
<td>1 m</td>
</tr>
<tr>
<td><strong>Adiab</strong></td>
<td>0.2 m</td>
</tr>
<tr>
<td><strong>Cond.</strong></td>
<td>0.8 m</td>
</tr>
<tr>
<td><strong>Evaporator Wall Interfacial HTC</strong> <em>:</em></td>
<td>$10^5$ W/m²K⁻¹</td>
</tr>
<tr>
<td><strong>Condenser Wall Temperature</strong></td>
<td>750 K</td>
</tr>
</tbody>
</table>

*Assumed gas gap between monolith and HP of ~ 0.5 mm
Steady State Results

Monolith Steady State Temperature:

Plane Z = 0

Plane X = 0
Steady State Results

SS temp of monolith along X-axis

*Trends imply temp distributions are symmetrical across monolith

SS temp of monolith along Y-axis
## Steady State Analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Element Type</th>
<th>Heating Power (kW)</th>
<th>Evaporator Wall HTC (W/m²K⁻¹)</th>
<th>Condenser Wall Boundary Conditions</th>
<th>HP Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>HEX20</td>
<td>75</td>
<td>$10^5$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>HEX8</td>
<td>75</td>
<td>$10^5$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>HEX27</td>
<td>75</td>
<td>$10^5$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>HEX20</td>
<td>100</td>
<td>$10^5$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>HEX20</td>
<td>75</td>
<td>$10^3$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>HEX20</td>
<td>75</td>
<td>$10^7$</td>
<td>750 K</td>
<td>None</td>
</tr>
<tr>
<td>6</td>
<td>HEX20</td>
<td>75</td>
<td>$10^5$</td>
<td>730 K</td>
<td>None</td>
</tr>
</tbody>
</table>

*HEX = x-node hexahedral element*
HEX Nodal Background

- HEX8 = 8-node trilinear hexahedral element
- HEX20/27 = 20-node and 27-node quadratic hexahedral elements
- More nodes results in higher simulation accuracy but slows computing process
- Increasing # nodes no longer affects accuracy past a certain point
- HEX20 is best option for high-precision simulation
### Steady State Analysis

#### Monolith Steady State Temperature:

1. **Cases 0-2**
   - **HEX8**: $75 \times 10^5$ Hz, $750$ K
   - **HEX27**: $75 \times 10^5$ Hz, $750$ K
   - **HEX20**: $100 \times 10^5$ Hz, $750$ K

2. **Cases 0, 3**
   - **HEX8**: $75 \times 10^5$ Hz, $750$ K
Steady State Analysis

Cases 0, 4, 5

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat Pipe Type</th>
<th>Length (m)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>HEX20</td>
<td>75</td>
<td>$10^3$</td>
</tr>
<tr>
<td>5</td>
<td>HEX20</td>
<td>75</td>
<td>$10^7$</td>
</tr>
<tr>
<td>6</td>
<td>HEX20</td>
<td>75</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

Cases 0, 6

Heat Pipe Microreactor Research
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## Case 1-5 Transient Cases

### Proposed Cases:

<table>
<thead>
<tr>
<th>Description</th>
<th>HTC (W/m²K)</th>
<th>SS Transfer</th>
<th>100s (HP Fail)</th>
<th>20000s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>No heat pipe failure</td>
<td>100000</td>
<td>100000</td>
<td>100000</td>
</tr>
<tr>
<td>*base case</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>HP 1 Failure</td>
<td>100000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>*center hp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>HP 1-7 Failure</td>
<td>100000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>*center, first ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
<td>HP 1-19 Failure</td>
<td>100000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>*center, 2 rings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 5</td>
<td>HP 1-37 Failure</td>
<td>100000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>*entire monolith</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Assumption: Case fail when T > 1500 K*
**Case 1-5:**

Maximum Fuel Temperature

Average Fuel Temperature

*Trend across average and max fuel temperature are generally similar as expected*
Monolith Temperature Results

Case 1-4:

Maximum Monolith Temperature

Average Monolith Temperature

*Trend across average and max monolith temperature are generally similar as expected*
Case 1-4: T_Solid Temp

*X-Axial data plot line runs along the x axis through monolith center

Example:

Heat Pipe Microreactor Research
Case 3 Temperature Distributions

*Heat Pipe Temperature cut along the y plane

*Monolith Temperature cut along the y plane

*Monolith Temperature cut along the x plane

*Take note of temperature scales, vary significantly between cases

*Visuals constructed using Paraview
Case 3 Calculation Results

**Average Temp of First 3 HP**

- Temperature (K)
  - 750.0
  - 750.5
  - 751.0
  - 751.5
  - 752.0
  - 752.5
  - 753.0

- Time (s)
  - 0
  - 5000
  - 10000
  - 15000
  - 20000

**Energy Transfer of First 3 HP**

- Energy (J)
  - 0
  - 50
  - 100
  - 150
  - 200

- Time (s)
  - 0
  - 5000
  - 10000
  - 15000
  - 20000

Heat Pipe Microreactor Research
Case 5 Temperature Distributions

*Take note of temperature scales, vary significantly between cases

*Heat Pipe Temperature cut along the y plane

*Monolith Temperature cut along the y plane

*Monolith Temperature cut along the x plane

*Visuals constructed using Paraview
Case 5 Calculation Results

Average Temp of First 3 HP

Energy Transfer of First 3 HP
### Proposed Cases:

<table>
<thead>
<tr>
<th>Description</th>
<th>Starting Time (s)</th>
<th>Ending Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC (W/m²K-1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>No heat pipe failure</td>
<td>N/A</td>
</tr>
<tr>
<td>Case 3 *base case</td>
<td>Base Case</td>
<td>0</td>
</tr>
<tr>
<td>Case 6</td>
<td>***</td>
<td>400</td>
</tr>
<tr>
<td>Case 7</td>
<td>***</td>
<td>1900</td>
</tr>
<tr>
<td>Case 8</td>
<td>***</td>
<td>9900</td>
</tr>
</tbody>
</table>

- **Assumption**: Case fail when T > 1500 K

---

**Case 3** is the same as case 3 with different failure times.

---

Heat Pipe Microreactor Research
Fuel Temperature Results

Case 1, 3, 6-8:

Maximum Fuel Temperature

Average Fuel Temperature

*Trend across average and max fuel temperature are generally similar as expected

Heat Pipe Microreactor Research
Monolith Temperature Results

Case 1, 3, 6-8:

Maximum Monolith Temperature

Average Monolith Temperature

*Trend across average and max monolith temperature are generally similar as expected*
Gen IV International Forum
Case 3, 6, 7, 8 Comparison

AT 5000s:

Case 3
Case 6
Case 7
Case 8

Heat Pipe Microreactor Research
Case 1, 3, 6-8:

**T_Solid Temp**

- Case 3 HP
- Case 1 HP
- Case 8 HP
- Case 6 HP
- Case 7 HP
- Case 3
- Case 7
- Case 8
- Case 6
- Case 1

*X-Axial data plot line runs along the x axis through monolith center

Example:
Case 8 Temperature Distributions

*Heat Pipe Temperature cut along the y plane

*Monolith Temperature cut along the y plane

*Monolith Temperature cut along the x plane

*Take note of temperature scales, vary significantly between cases

*Visuals constructed using Paraview
Case 8 Calculation Results

Average Temp of First 3 HP

Energy Transfer of First 3 HP

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General Conclusions/Observations

• SAM/MOOSE coupling successfully applied to the heat pipe microreactor;
• Heat pipes transfer the energy from core to secondary side well;
• Sensitivity analysis test a few critical thermal hydraulic parameters;
• Heat pipe failures can challenge the monolith integrity.
Summary

• Current contribution:
  – Heat Pipe model using SAM/MOOSE coupling
  – MAGNET - Steady state and transient results

• Future projects:
  – Couple HP to heat exchanger with secondary loop
  – Develop more detailed heat pipe model
  – Couple to neutronics and thermal hydraulics
Acknowledgement

• Funding from DOE NEUP Program CFA-21-24226

• Functional and Operating Requirements for the Microreactor Agile Non-Nuclear Experimental Test Bed (MAGNET) – Idaho National Lab – Dr. Morton

• Consultation in using SAM for analysis - Argonne National Lab – Drs. R. Hu and G.J.Hu
## Upcoming Webinars

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<th>Presenter</th>
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<tr>
<td>15 December 2021</td>
<td>Development of an Austenitic/Martensitic Gradient Steel by Additive Manufacturing</td>
<td>Dr. Flore Villaret, EDF, France Winner of the Pitch Your PhD Contest</td>
</tr>
<tr>
<td>27 January 2022</td>
<td>ESFR SMART a European Sodium Fast Reactor Concept including the European Feedback Experience and the New Safety Commitments following Fukushima Accident</td>
<td>Mr. Joel Guidez, CEA, France</td>
</tr>
<tr>
<td>24 February 2022</td>
<td>Artificial Intelligence in Support of Nuclear Energy Sector</td>
<td>Prof. Prinja Nawal, Jacobs, UK</td>
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