INL/MIS-25-83758-Revision-0

Heat Pipe Modeling with Sockeye

August 2025

Changing the World's Energy Future

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Idaho National Laboratory

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Sockeye

Heat Pipe Modeling with Sockeye

Symposium: The heat pipe, the microreactor, and space
University of Stuttgart

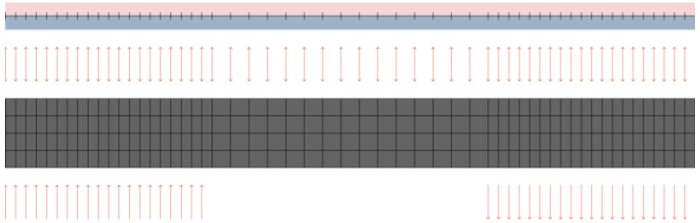
Sockeye Introduction

- Engineering scale heat pipe application for the analysis of heat pipes in microreactors.
  - Focus is on high-temperature, cylindrical heat pipes with screen/mesh wicks.
  - Supported working fluids: sodium, potassium, water
- Based on the MOOSE framework:
  - Finite element framework upon which many relevant applications are based:
    - Griffin: Radiation transport
    - BISON: Thermomechanics
    - Pronghorn: Fluid mechanics
  - Relatively simple coupling to other MOOSE-based applications.

Capabilities Overview

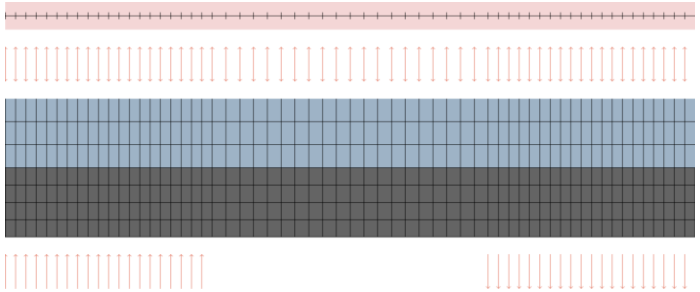
Two-Phase Flow Model

1D two-phase flow



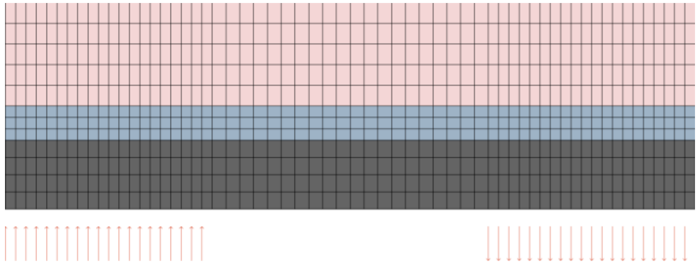
Liquid-Conduction, Vapor-Flow Model

1D single-phase flow



Conduction Model

2D heat conduction



Two-Phase Flow Model

- Original heat pipe model in Sockeye.
- 1D (couples to 2D heat conduction in cladding).
- Uses the "7-equation model" for two-phase flow.
  - 7 PDEs: 2 mass, 2 momentum, 2 energy, 1 volume fraction.
  - Both phases treated as compressible.
  - Each phase has its own pressure.
  - Well-posed model.
- Discretized using the finite volume method with HLLC flux computation.
- Has robustness issues:
  - Startup (fluid properties space not as robust in low-pressure range).
  - Phase disappearance issues (condenser pool, dryout).

Liquid-Conduction, Vapor-Flow (LCVF) Model

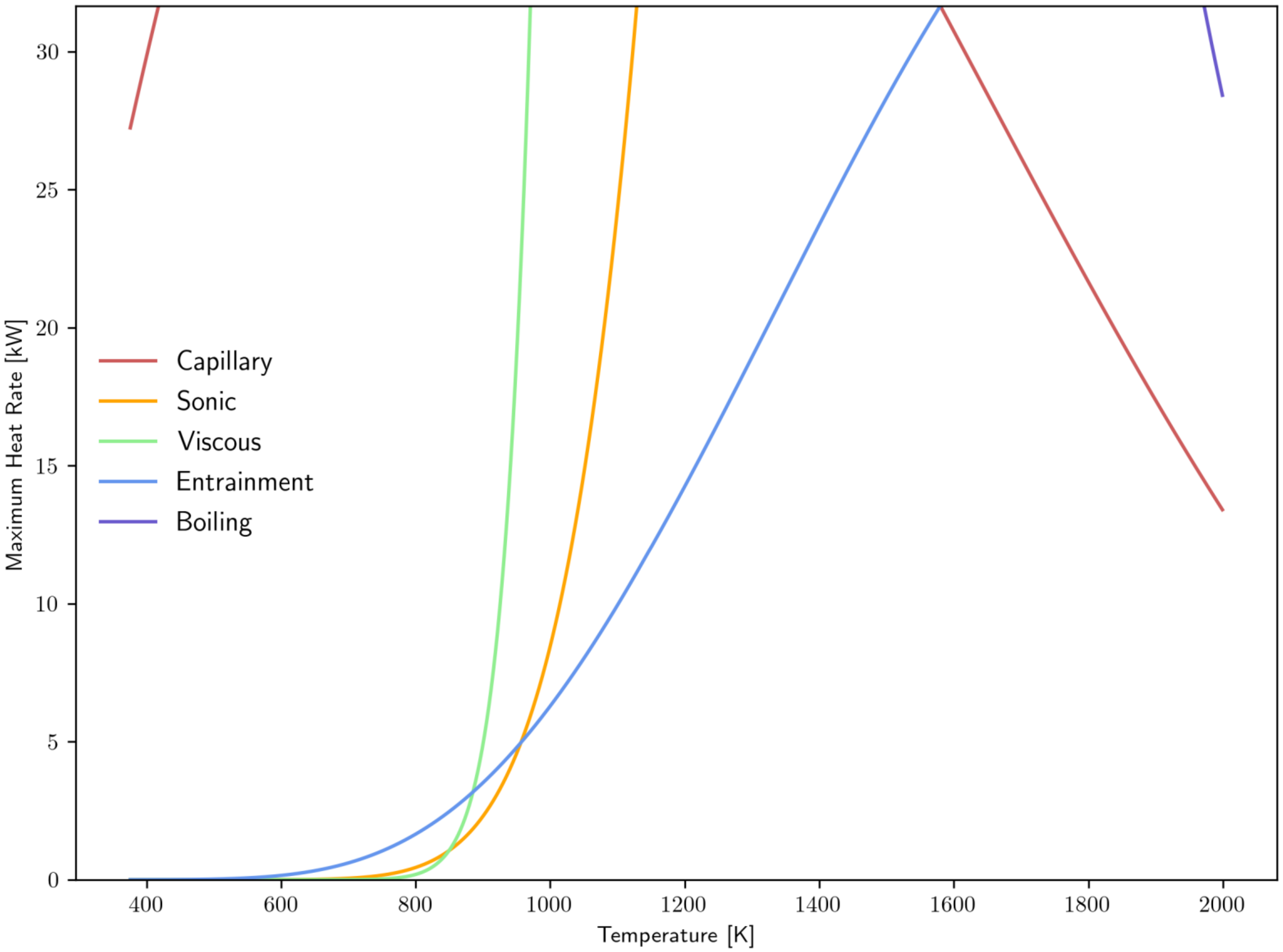
- Newest heat pipe model (created in FY23).
- 1D vapor flow coupled to 2D heat conduction in wick (and optionally cladding).
- Uses the Euler equations of gas dynamics for the vapor flow.
  - 3 PDEs: mass, momentum, energy.
  - Compressible.
- Liquid phase approximated analytically with steady assumptions at the current power.
  - Used for detecting capillary limit.
- Discretized using the finite volume method with HLLC flux computation.

Conduction Model

- 2D heat conduction for the entire heat pipe domain (cladding, wick, and core).
  - Cladding and liquid/wick use actual thermal properties.
  - Vapor core uses *effective* thermal conductivity to approximate heat transfer.
- Limits are incorporated by comparing current power to analytic limits.
  - Core thermal conductivity controlled to enforce limits.

Heat Pipe Limits

- Designers often consult analytic expressions of various heat pipe limits
- Typically give maximum heat rate through heat pipe vs. some reference temperatures
- Operating space is area under all curves



Heat Pipe Limits

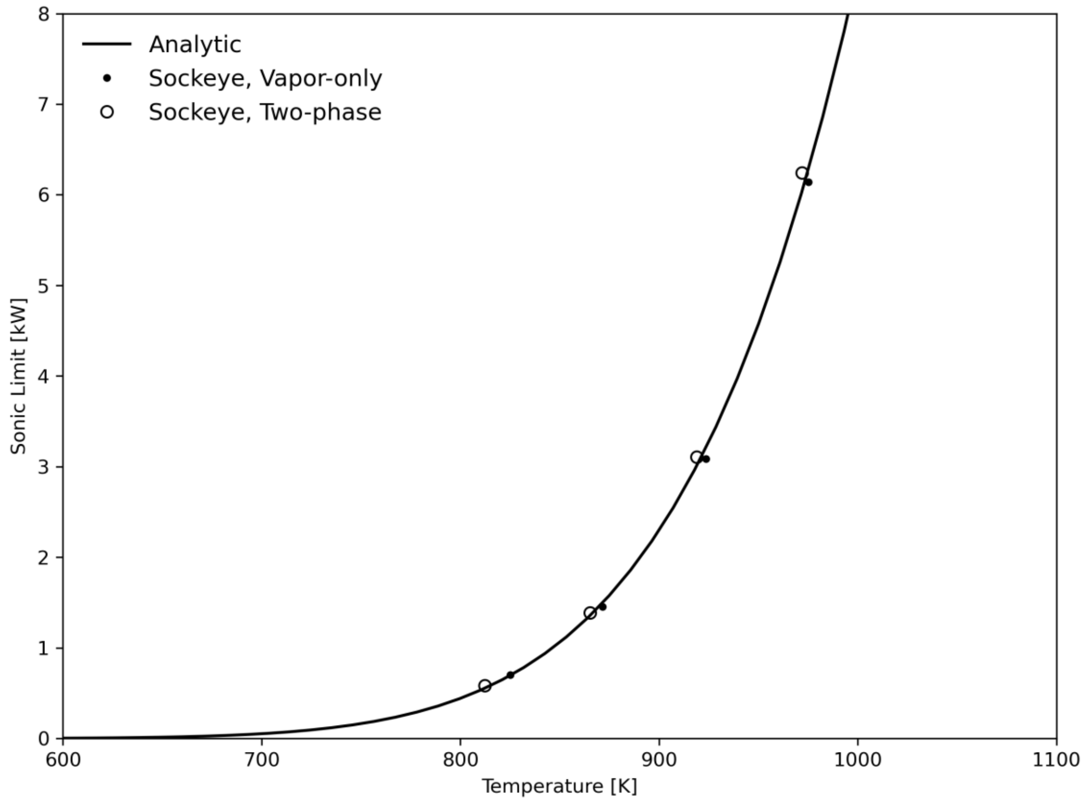
- While reliable, they must be used within some limits
  - Various fluid mechanics limit heat throughput
- **Capillary limit**: The capillary pressure may be insufficient to sustain the pressure drops around the heat pipe circuit.
- **Viscous limit**: Viscous drag in vapor may prevent movement to condenser end.
- **Sonic limit**: Vapor can be “choked” at evaporator exit, leading to a sonic bottleneck.
- **Entrainment limit**: Liquid can be sheared off wick surface into vapor core.
- **Boiling limit**: Excessive boiling at wall and in wick can impede capillary action, preventing liquid from returning to evaporator.

Modeling Limits

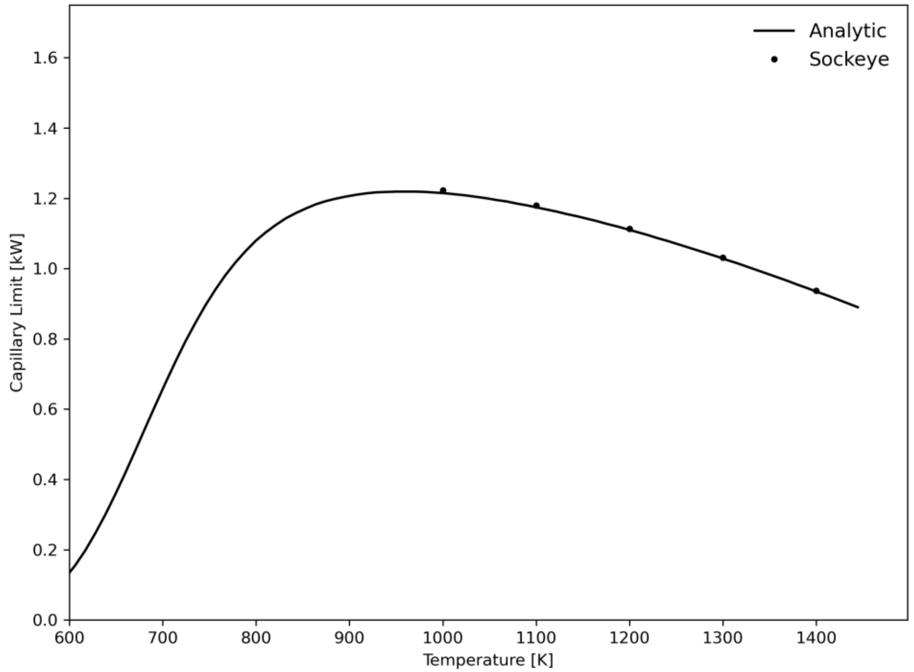
Limit	Two-Phase Model	Vapor-Only Model	Conduction Model	Notes
Capillary	Mechanistic	Mechanistic vapor, analytic liquid	Analytic	
Sonic	Mechanistic	Mechanistic	Analytic	
Viscous	Mechanistic	Mechanistic	Analytic	
Entrainment	Not considered	Not considered	Analytic	Believed not to be a concern for high-temperature HPs.
Boiling	Not considered	Not considered	Analytic	Requires very high radial heat flux; may not be worth modeling.

Limits Assessments

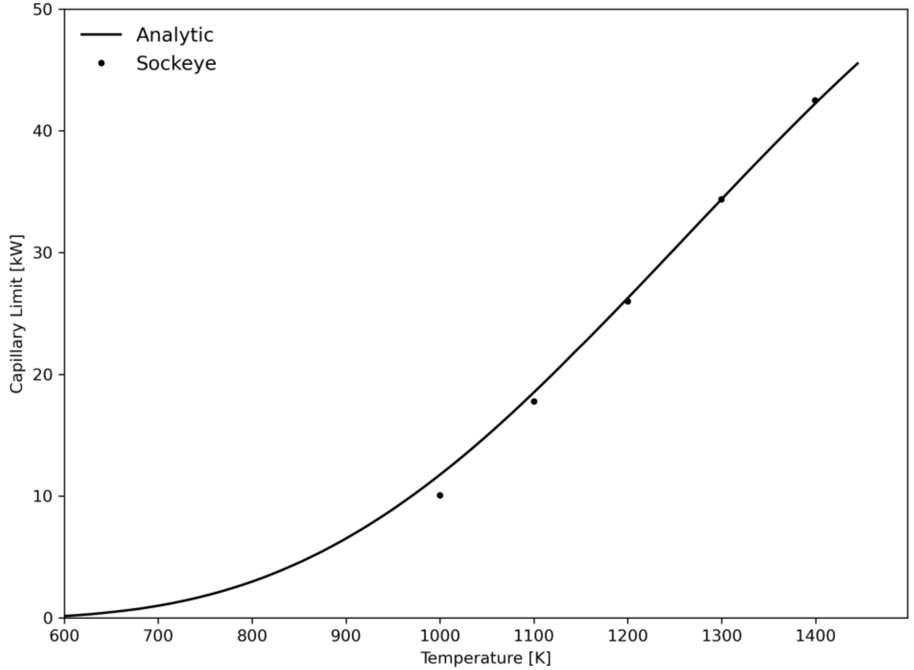
Sonic Limit



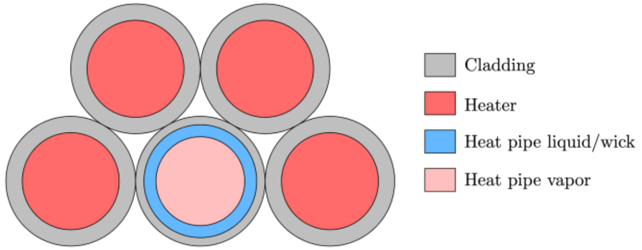
Capillary Limit,
Homogeneous Wick



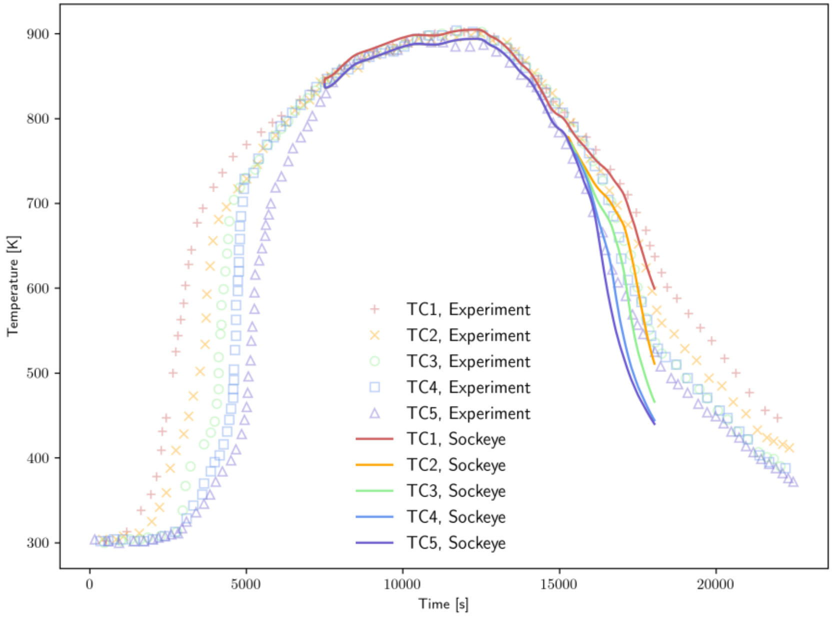
Capillary Limit,
Annular Wick



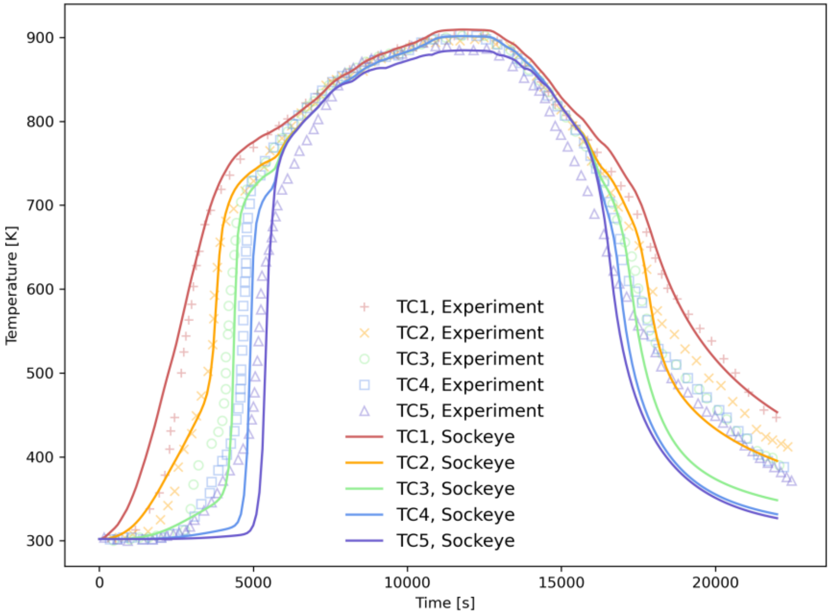
SAFE-30 Assessment



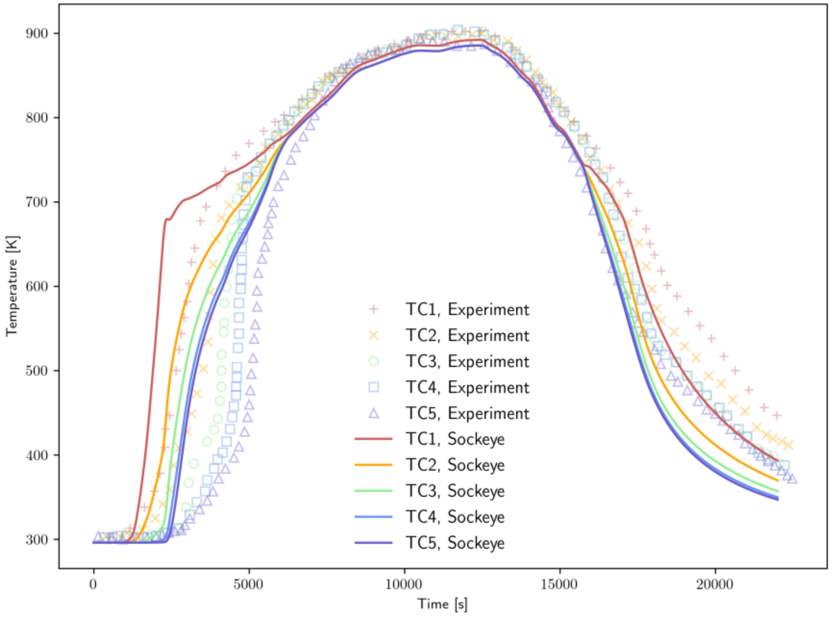
Two-Phase Flow Model



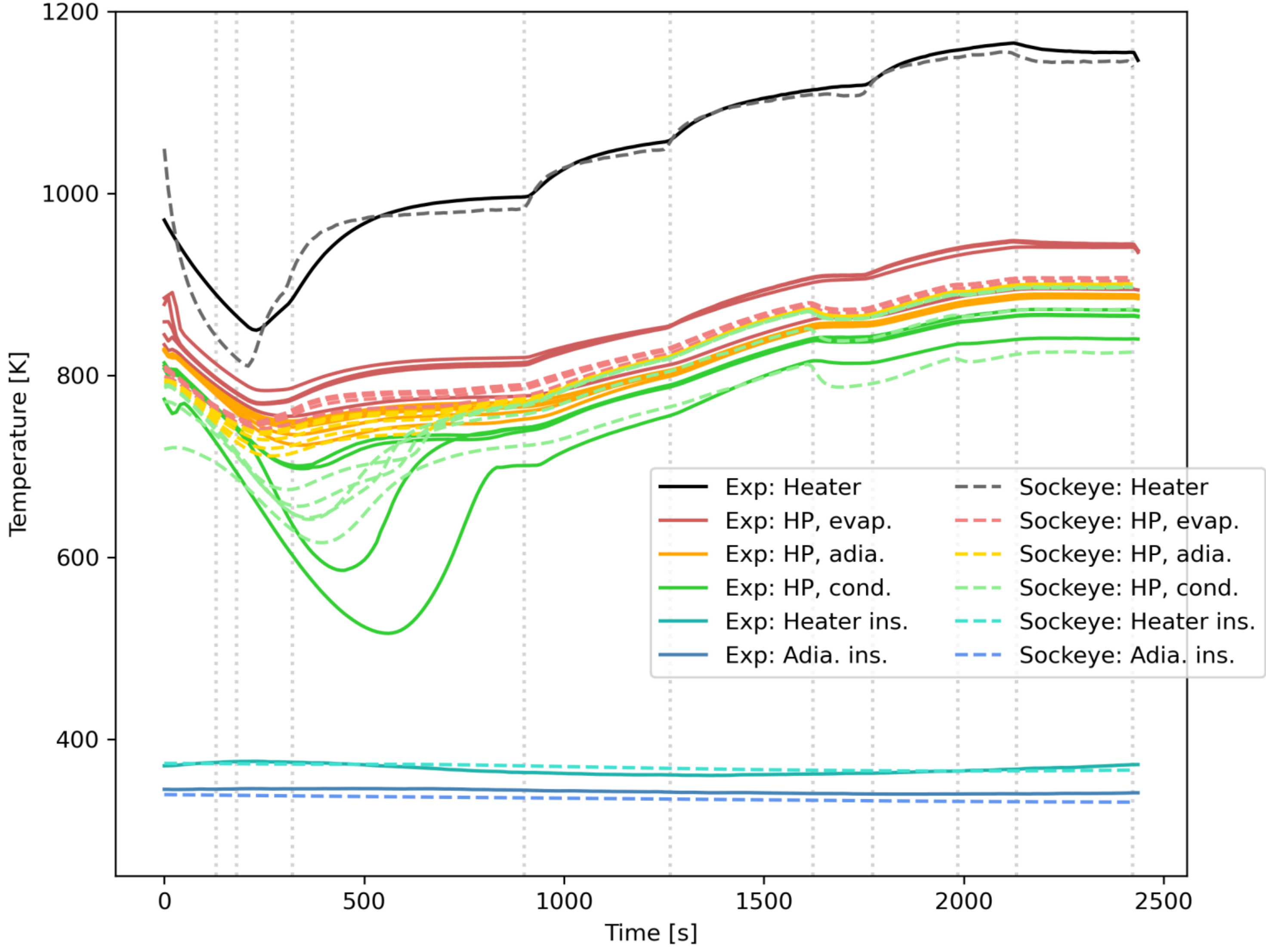
Vapor-Only Flow Model

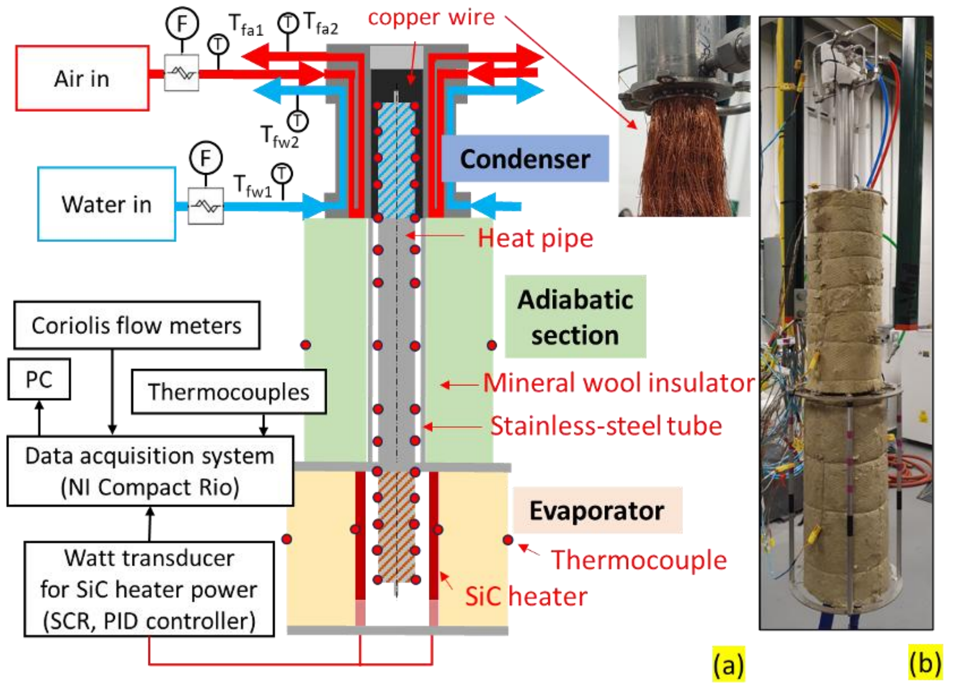


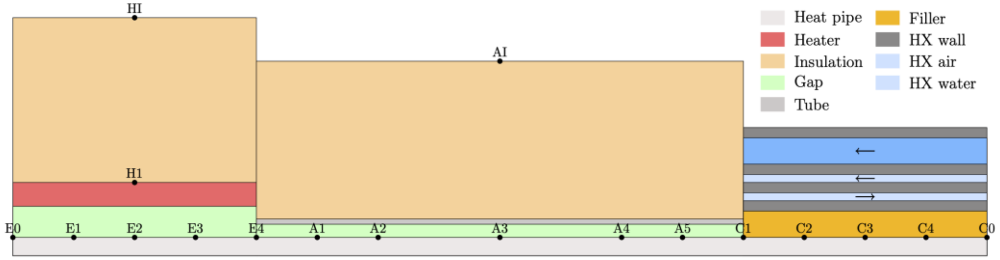
Conduction Model



MISOH1 Assessment







Conclusions

- Validation is difficult:
  - Model results for single-heat-pipe experiments are dominated by external heat transfer modeling:
    - What is the actual heat distribution along the pipe?
    - Large uncertainty in geometry, thermal properties, and boundary conditions of the system.
  - Sometimes difficult to understand experimental results.
    - For example, what is contributing to the pipe's inactive length?
- Validation needs:
  - Internal heat pipe data extremely useful when possible.
    - Distributed vapor temperature is particularly useful.
  - Capillary limit measurement

Current and Future Work

- Current work:
  - Gas mixture model for non-condensable gases:
    - Adds to system a species transport partial differential equation:

$$\frac{\partial}{\partial t}(\xi \rho A) + \nabla \cdot (\xi \rho u A) + \nabla \cdot J = 0 \qquad J = -\rho D \nabla \xi$$

  - Mechanistic startup flow dynamics:
    - Transition from rarefied gas dynamics to continuum flow
- Possible future work:
  - Multidimensional, multiphase flow model
  - Thermosyphon support
  - Equation of state improvements

Idaho National Laboratory

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Applying for Sockeye

- Go to https://inl.gov/ncrc/.
- Click "Make/Manage Requests".
- Make NCRC account if you don't have one already, and then log in.
- Click "Request Licensed Software"
- Select "Sockeye" and then access level (1, 2, or 4).
  - Level 1: Binary on INL HPC only.
  - Level 2: Binary on any computer.
  - Level 4: Source.
  - Select "source" only if you need to modify source code or want to make direct contributions to the project.
- Sockeye is 810-controlled, so it can take months to be approved, particularly for non-U.S. citizens.