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Heat Pipe Modeling with Sockeye

November 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Computational Scientist

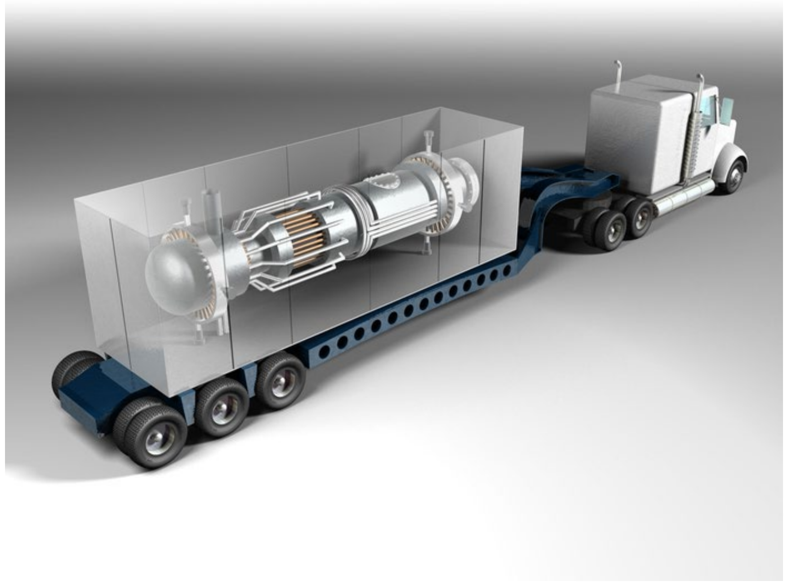
Sockeye

Heat Pipe Modeling with Sockeye

Code Seminar

Motivation

- Heat pipe modeling is a component of microreactor modeling
  - Many microreactor designs cooled by heat pipes
- Microreactors
  - Relatively small power output, up to 20 MWth
  - Relatively small physical size
  - Portable—entire unit transportable via truck, shipping container, plane, or rail
    - Can be installed in remote areas or areas of natural disaster for emergency power
    - Can be exchanged with “fresh” microreactors quickly
  - Factory fabricated, eliminating some difficulties of large-scale construction projects
    - Reduced capital cost



Rendering of a microreactor in a trailer truck. Image courtesy of U.S. DOE.

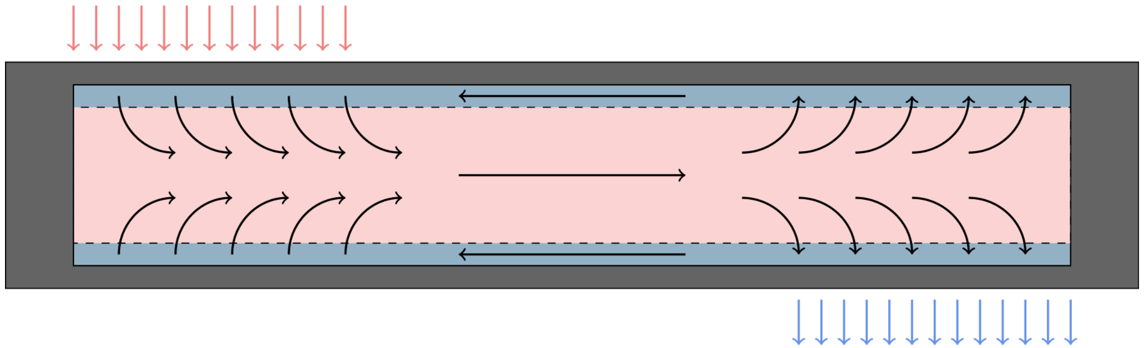
What Is a Heat Pipe?

- A heat pipe is a sealed tube containing working fluid and a wicking structure that transfers heat via an evaporation/condensation cycle.
- Desirable properties
  - Very efficient heat transfer
  - Near isothermal operation—little temperature drop over long distances
  - Passive, no moving parts
  - Compact cross section
- Used for a variety of applications
  - Electronics cooling
  - HVAC
  - Space applications
  - Permafrost cooling

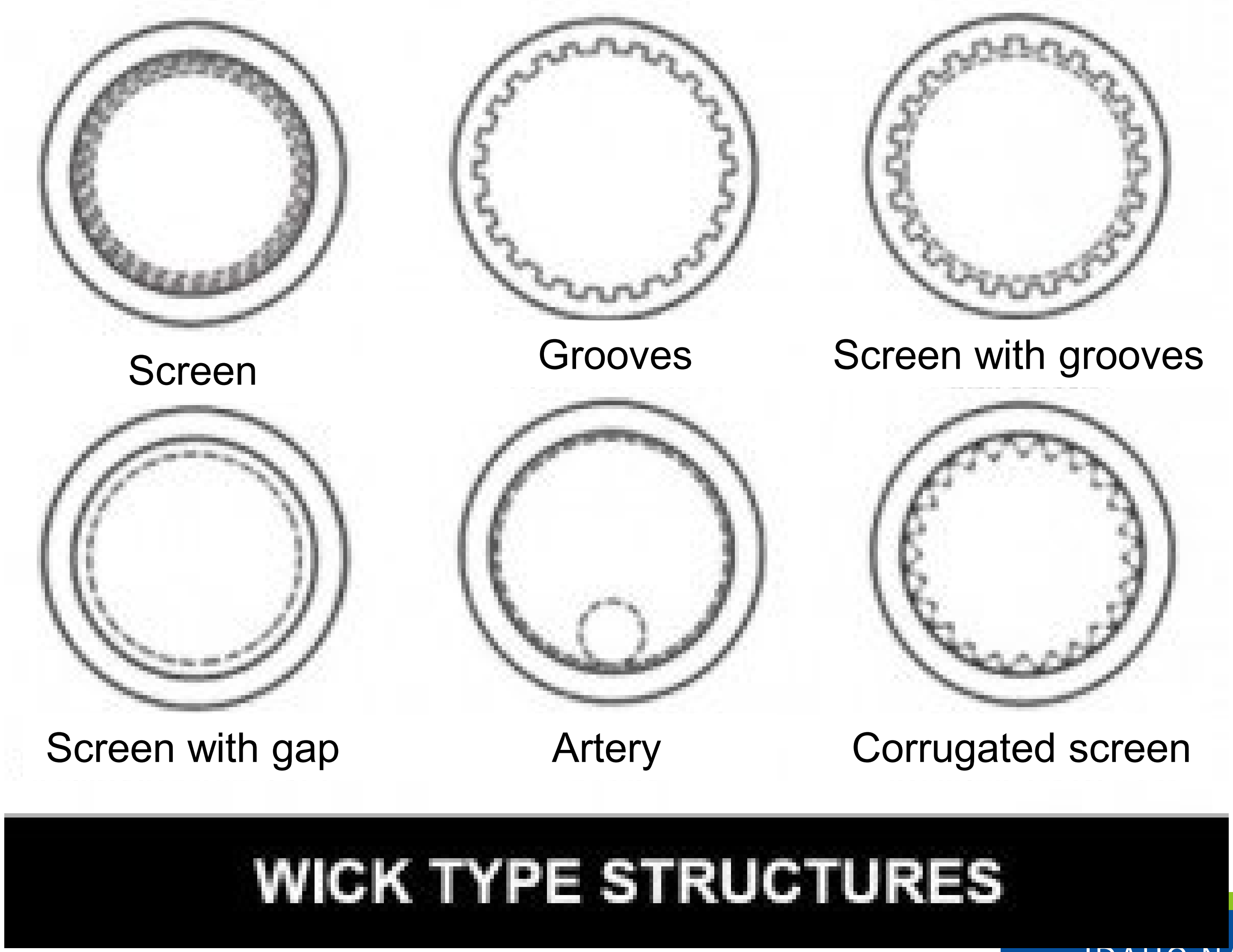
Trans-Alaska Pipeline

The Basics of Heat Pipe Operation

- Heat pipes operate on an evaporation/condensation cycle
  - Heat vaporizes working fluid in the *evaporator* end of the pipe
  - Vapor pressure gradient causes vapor to travel down length of heat pipe, passing through *adiabatic* section until it is cooled in the *condenser* section, condensing it and releasing its latent heat
  - Condensed fluid returns to the heated end
    - Thermosyphons must use gravity to do this
    - Heat pipes use capillary forces to do this, sometimes counter to gravity
  - Cycle begins again



Types of Wick Structures

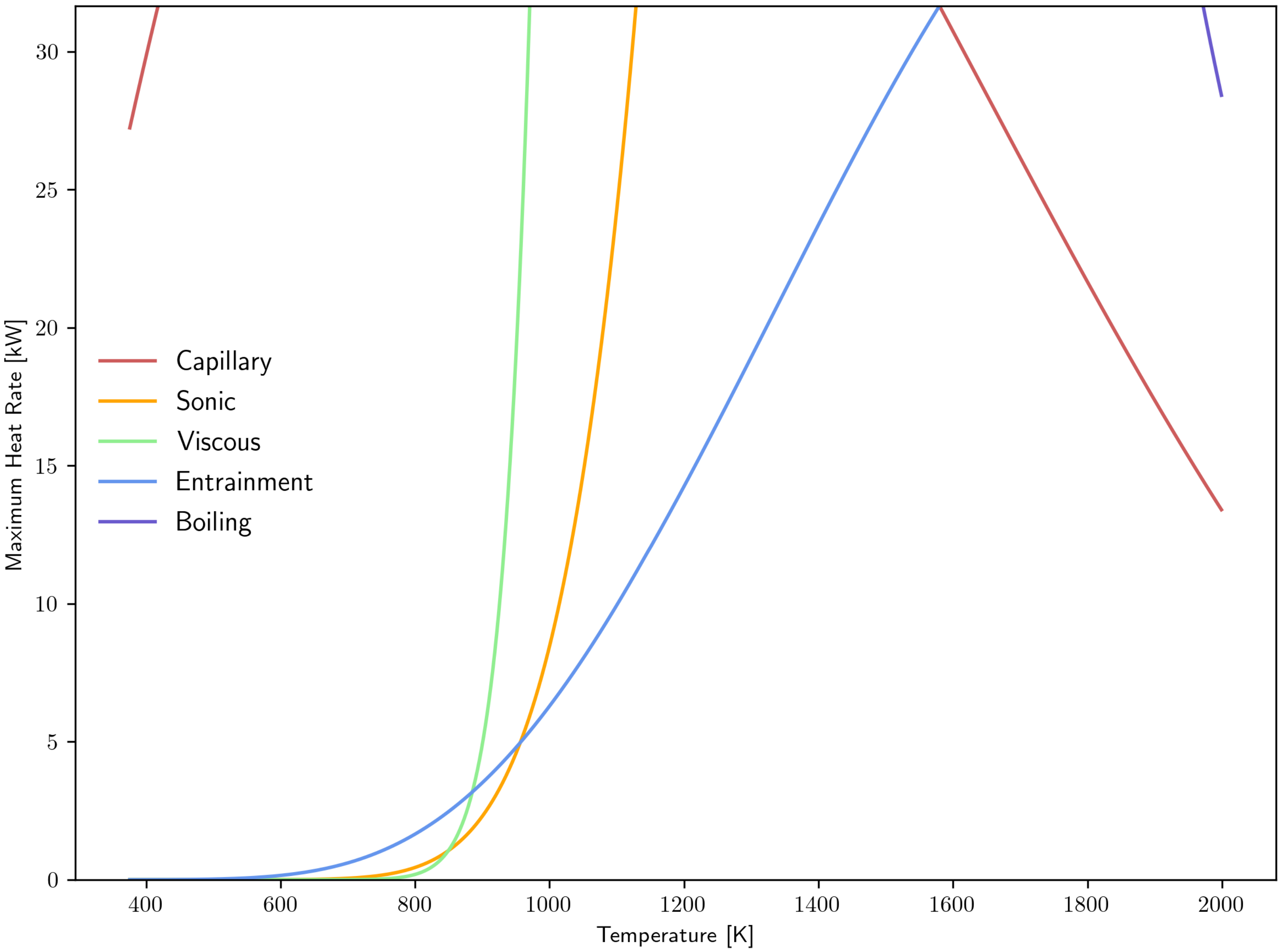


Heat Pipe Limits

- 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

Heat Pipe Limits

- Designers often employ 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



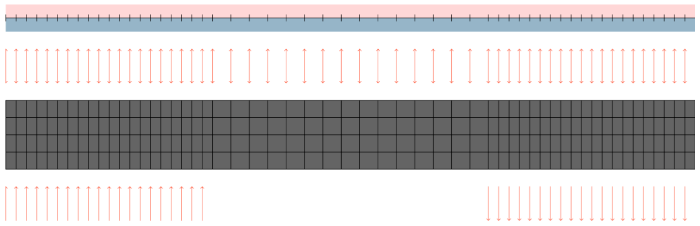
Sockeye Introduction

- Engineering scale heat pipe application for the analysis of heat pipes in microreactors
  - Focus is on high-temperature heat pipes
- Based on the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework
  - Relatively simple coupling to other MOOSE-based applications
- Funded by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program

Capabilities Overview

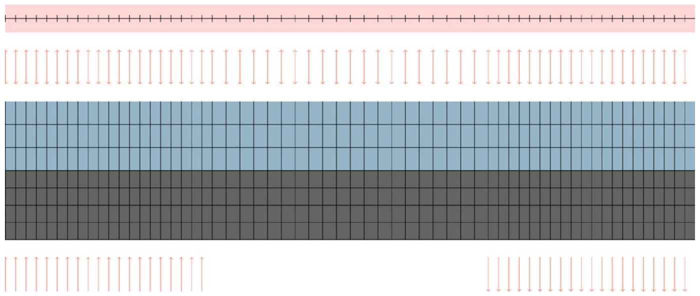
Two-Phase Flow Model

1D two-phase flow



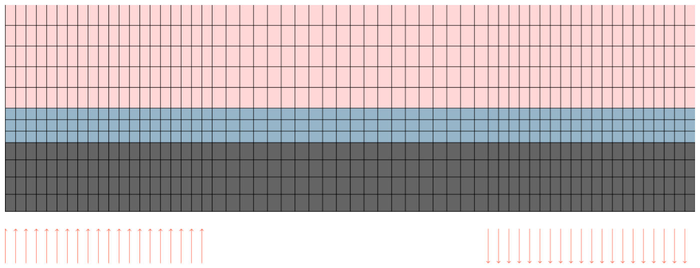
Vapor-Only Flow Model

1D single-phase flow



Conduction Model

2D heat conduction



Capabilities Comparison

Comparison	Two-Phase Flow Model	Vapor-Only Flow Model	Conduction Model
Accuracy: Startup	★★★	★★★	★
Accuracy: Normal Op.	★★★★★	★★★★	★★★
Accuracy: Dryout	★★★★★	★★★★	★★
Robustness: Startup	★	★★★★	★★★★★
Robustness: Normal Op.	★★★	★★★★★	★★★★★
Robustness: Pooling	★★	★★★★★	★★★★★
Robustness: Dryout	★★	★★★★★	★★★★★
Speed	★	★★★★	★★★★★
Simplicity	★	★★★	★★★★★
Tuning Required	None	None	Some

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)

Vapor-Only Flow Model

- Newest heat pipe model (created in Fiscal Year 2023)
- 1D vapor flow coupled to 2D heat conduction in wick (and optionally in 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

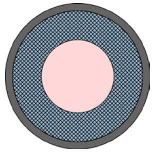
- 2D heat conduction for the entire heat pipe domain (cladding, wick, and core)
  - Cladding and wick use actual thermal properties
  - Core uses *effective* thermal conductivity to approximate heat transfer
- Limits are incorporated by comparing current power to analytic limits
  - Core thermal conductivity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

Modeling Limits

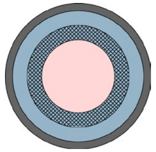
Limit	Two-Phase Flow Model	Vapor-Only Flow Model	Conduction Model	Notes
Capillary	Mechanistic	Mechanistic vapor, analytic liquid	Analytic	
Sonic	Mechanistic	Mechanistic	Analytic	
Viscous	Mechanistic	Mechanistic	Analytic	
Entrainment	Not considered	Not considered	Analytic	Believed not to be a concern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

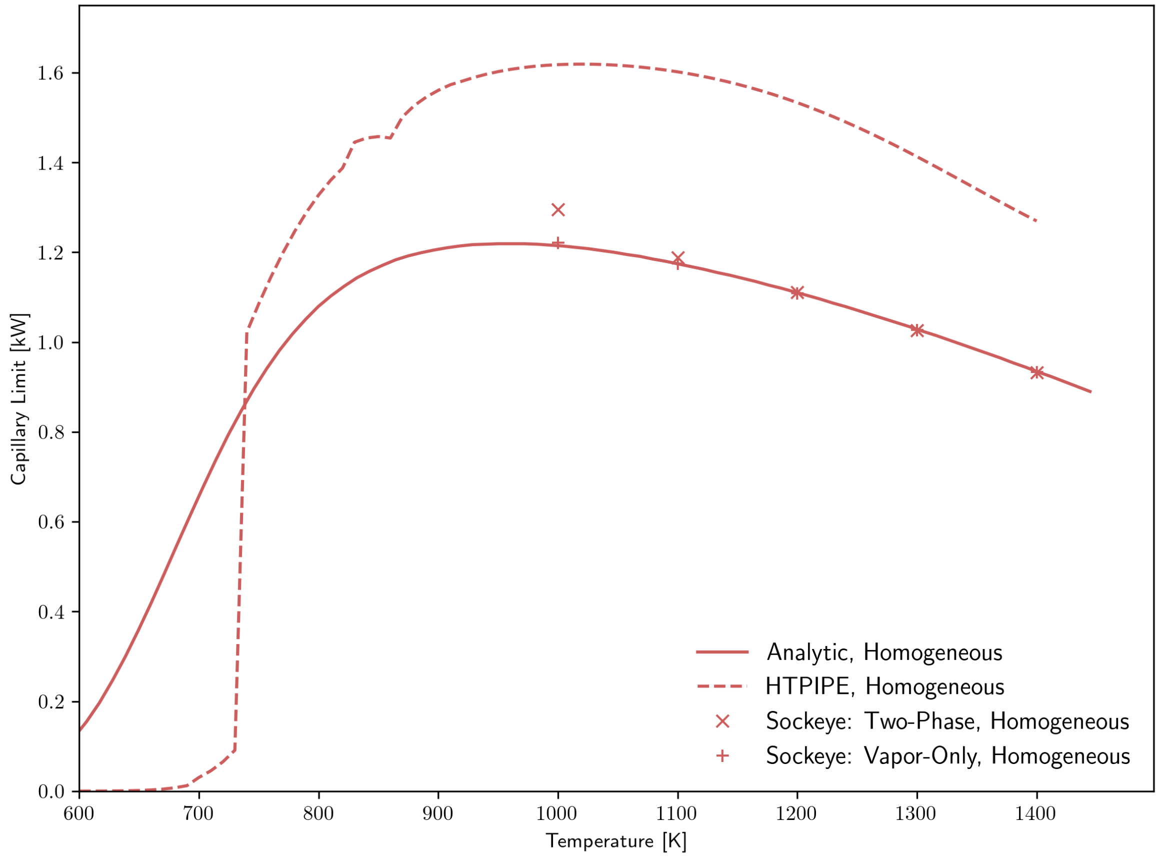
Capillary Limit Assessment

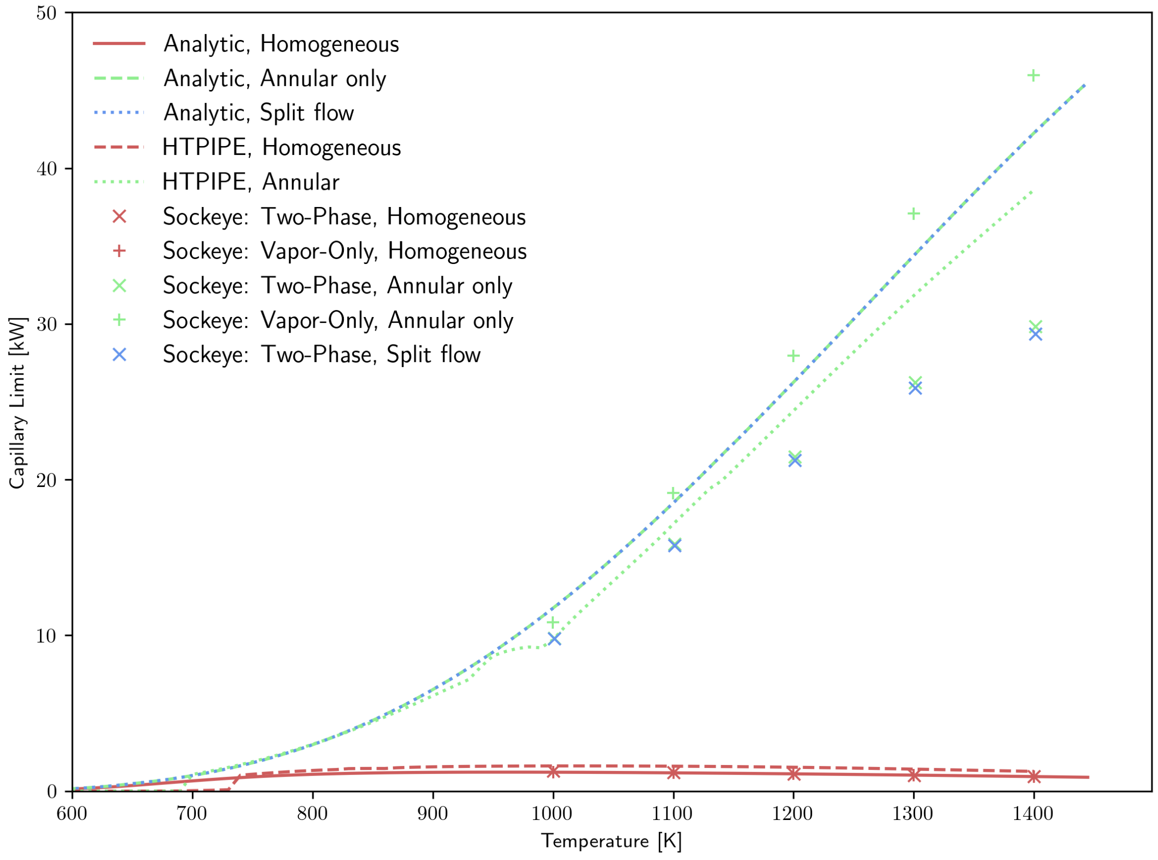
Homogeneous Wick



Annular Wick

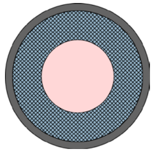


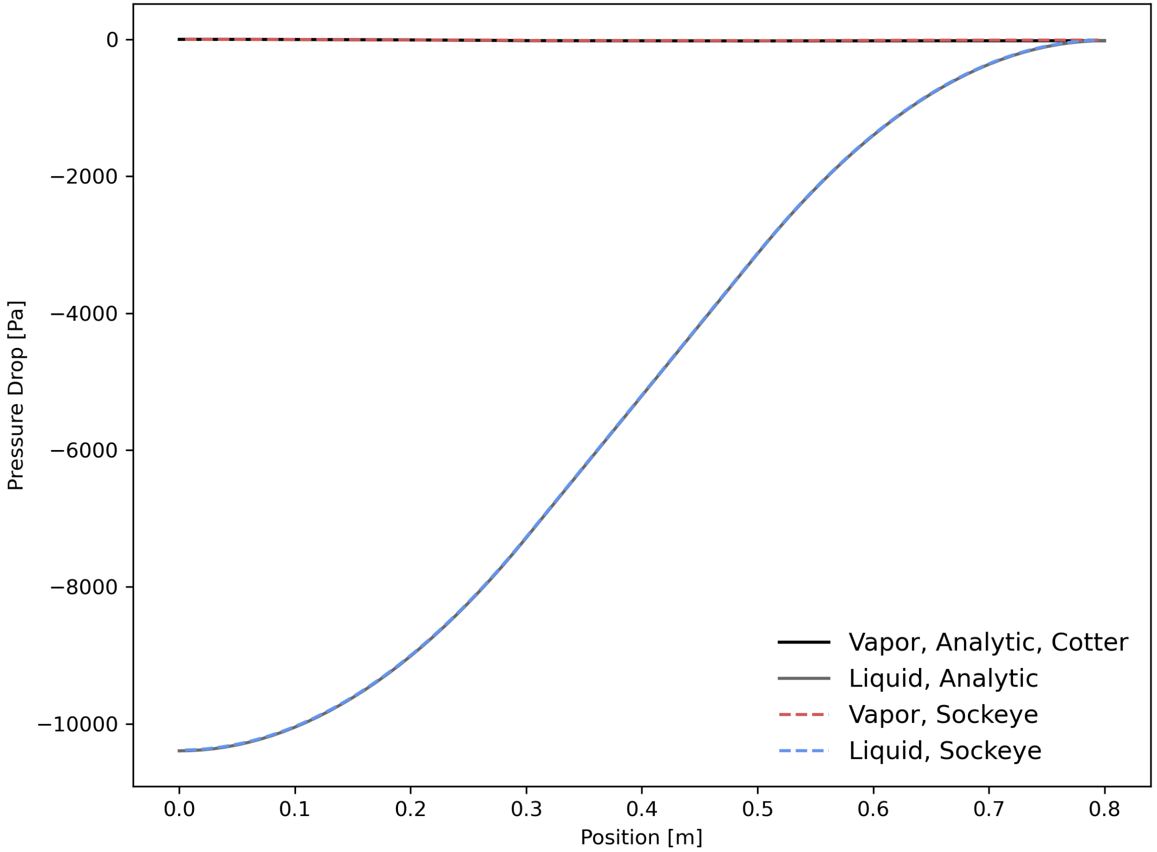




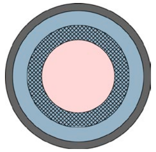
Capillary Limit Assessment (Continued)

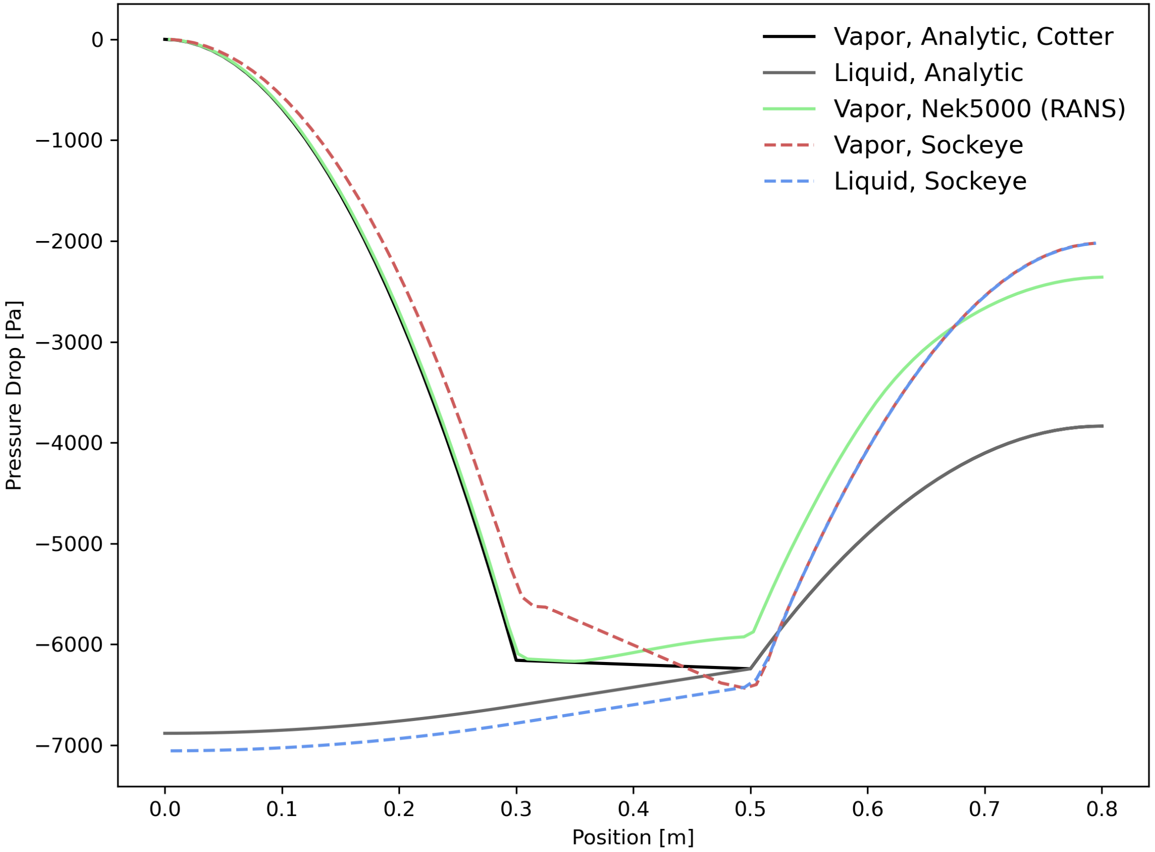
Homogeneous Wick



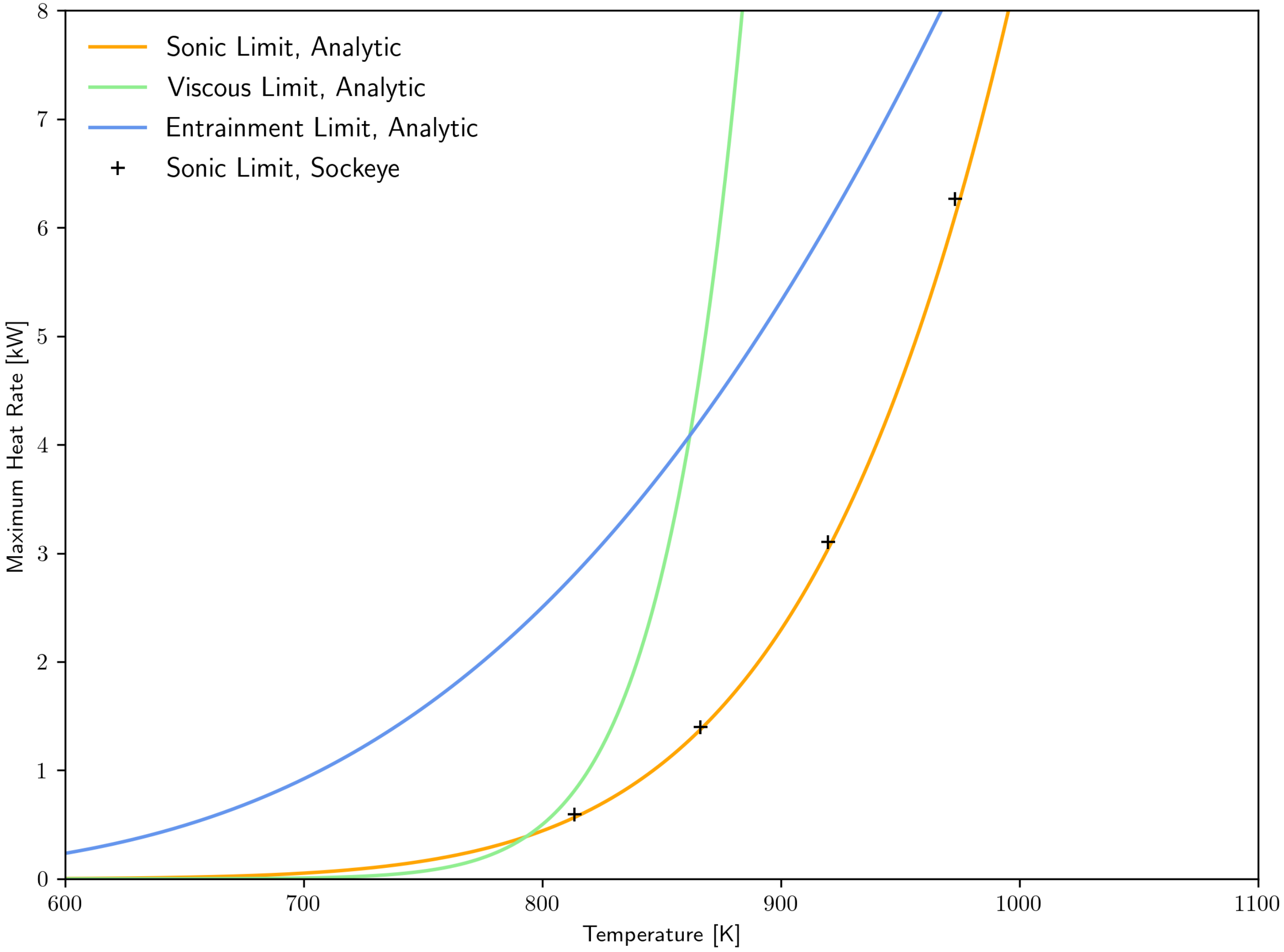


Annular Wick

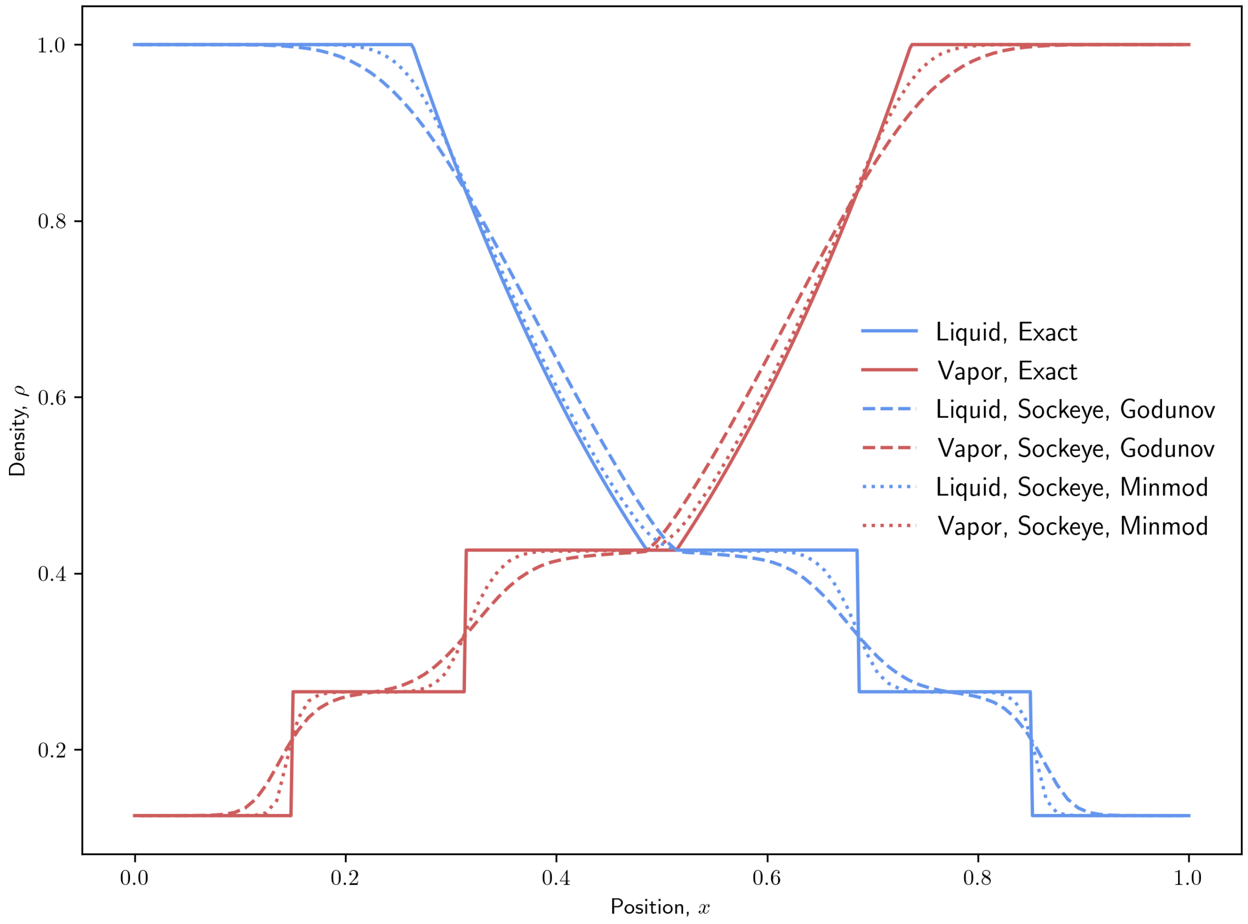


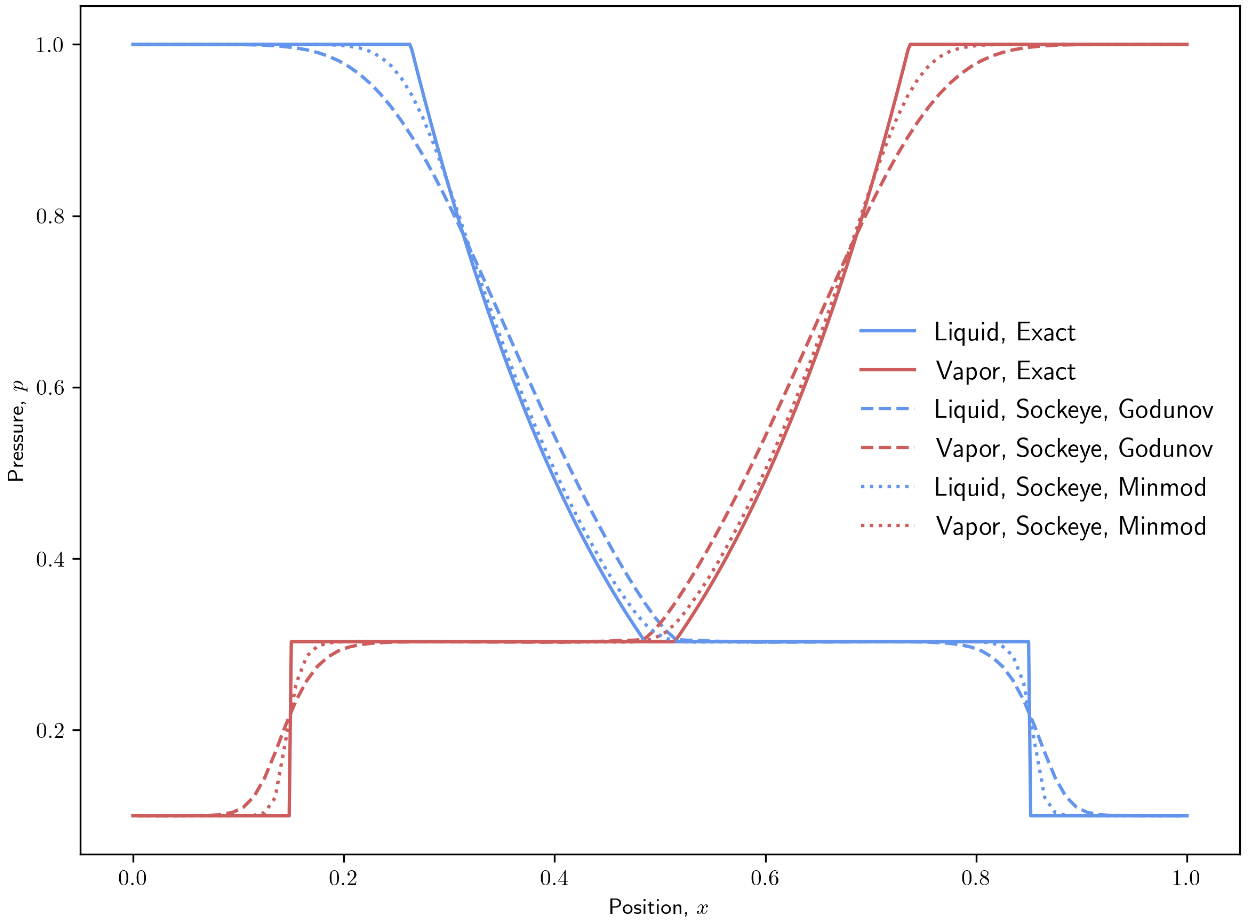


Sonic Limit Assessment



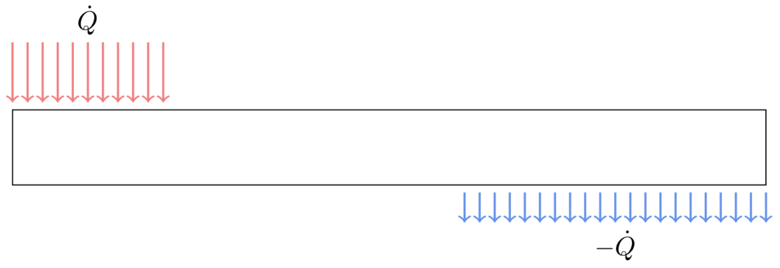
Sod Shock Tube Benchmark



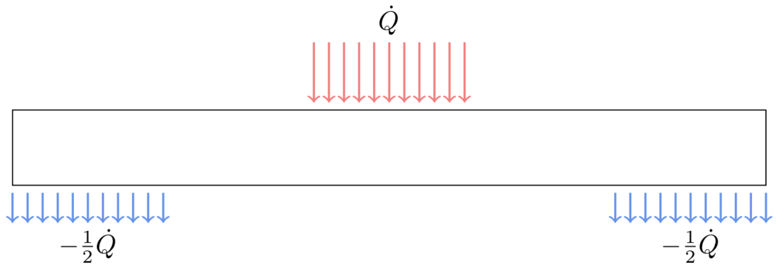


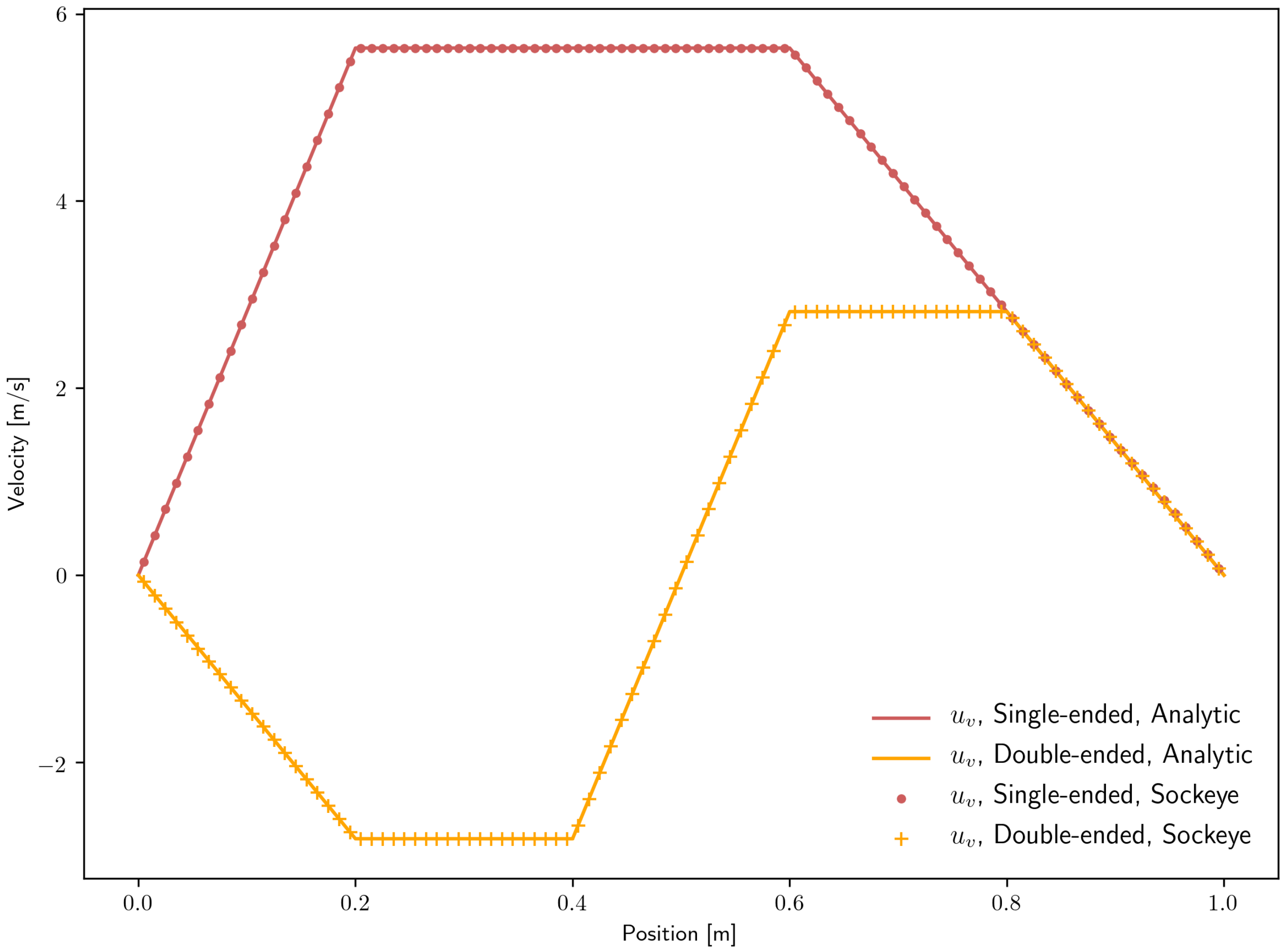
Comparison to Analytic Solutions

Single-Ended



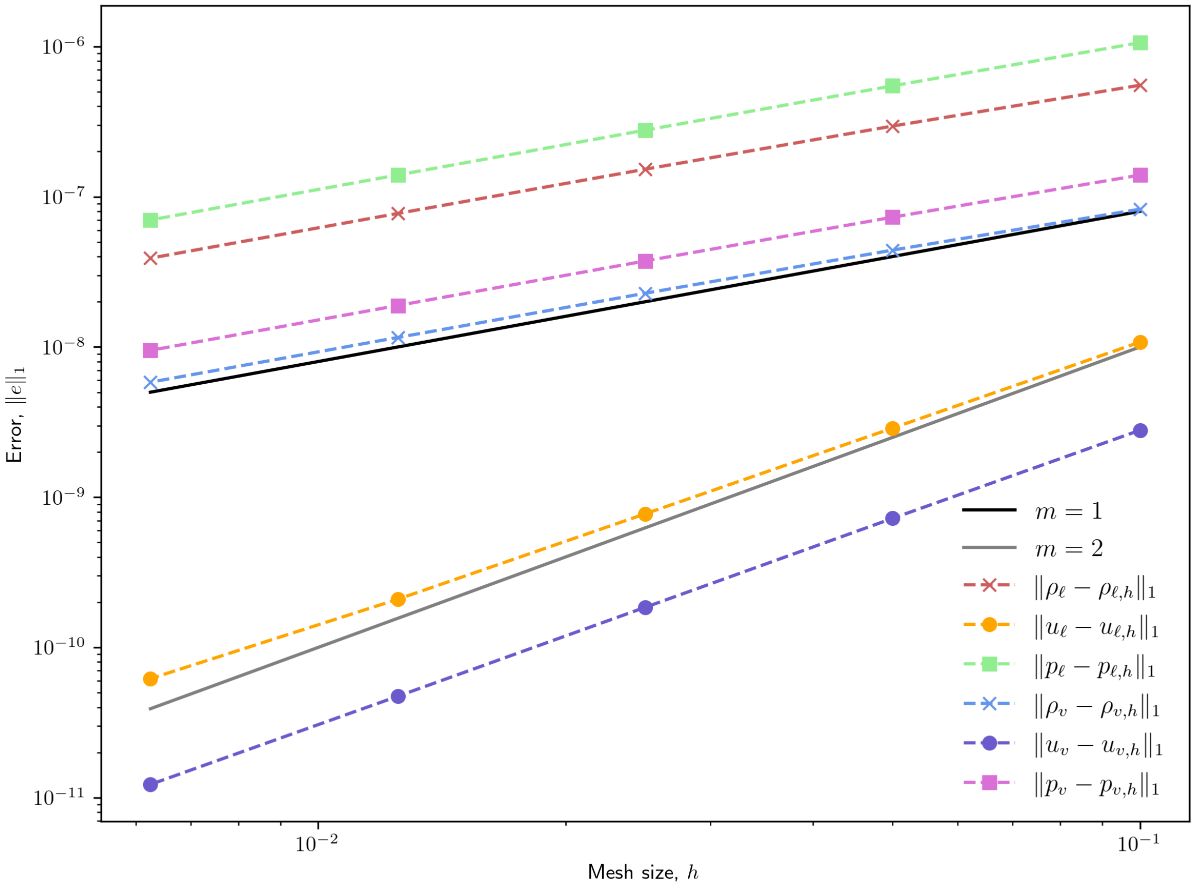
Double-Ended



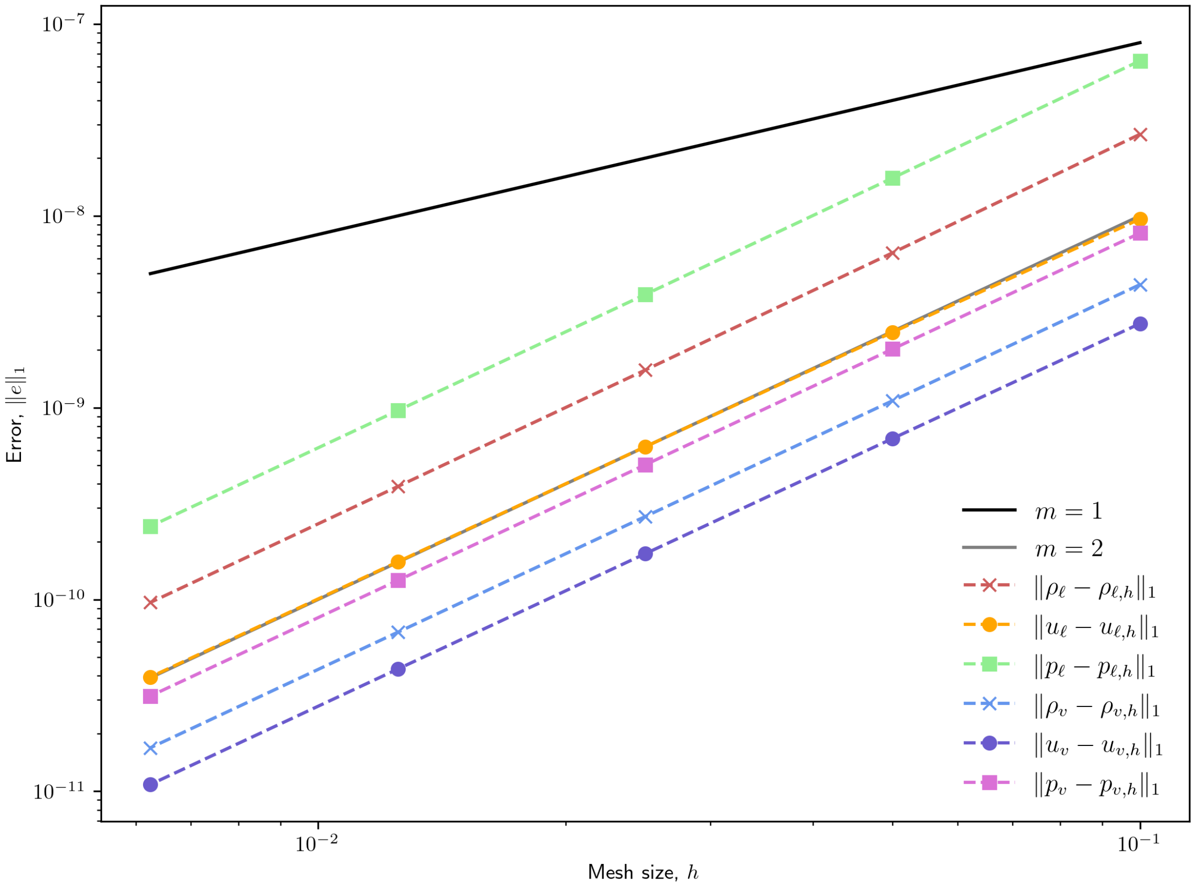


Spatial Convergence Verification

Godunov (1st-order scheme)

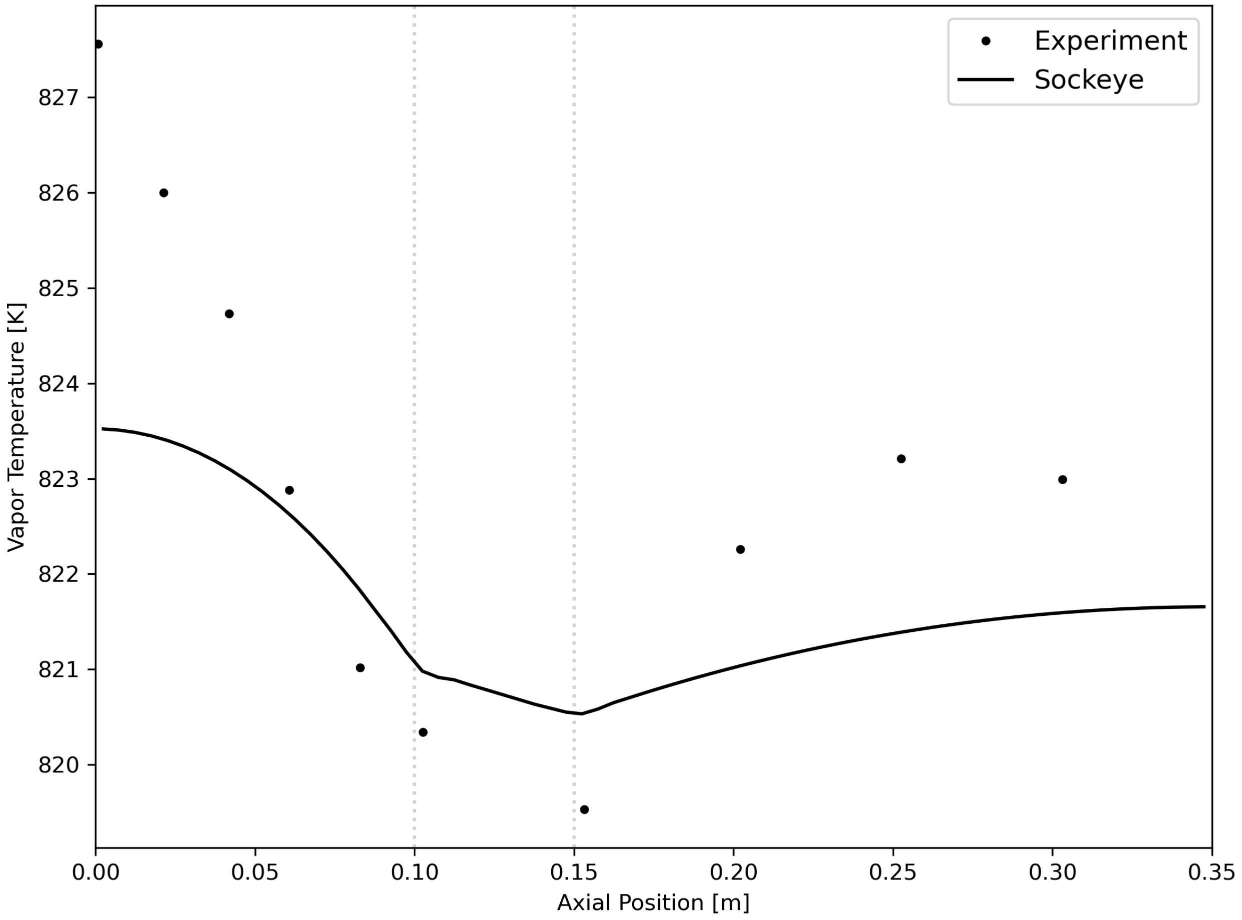


Slope Reconstruction (2nd-order scheme)

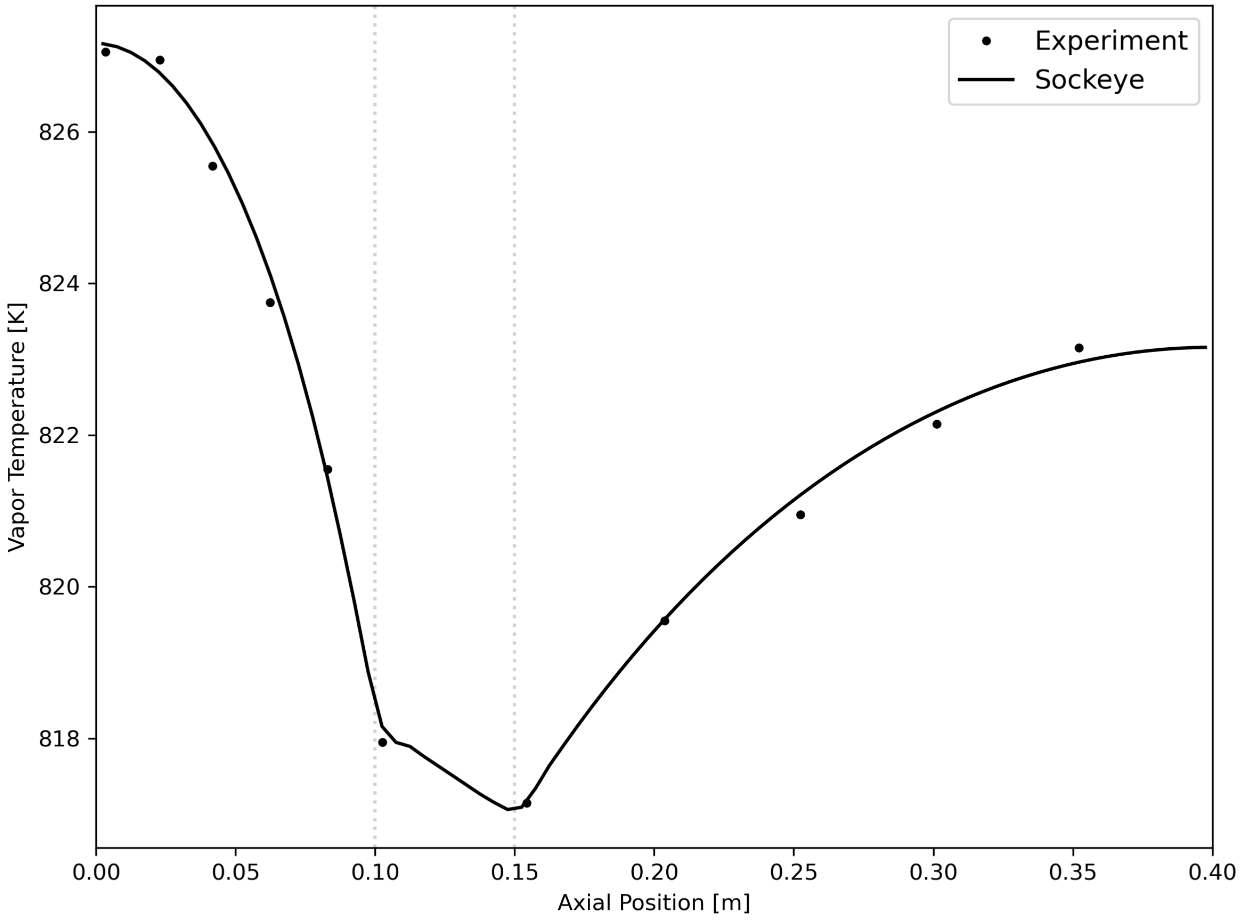


Ivanovskii Experiments

315 W

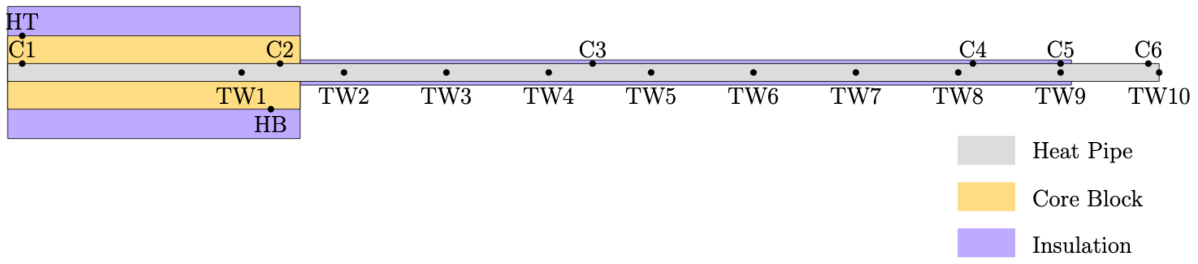


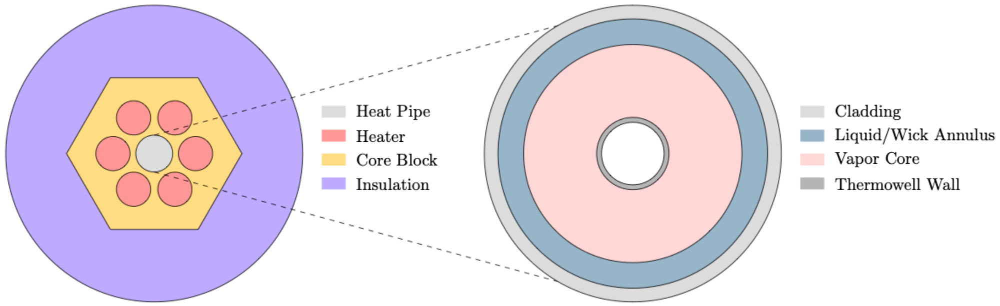
615 W

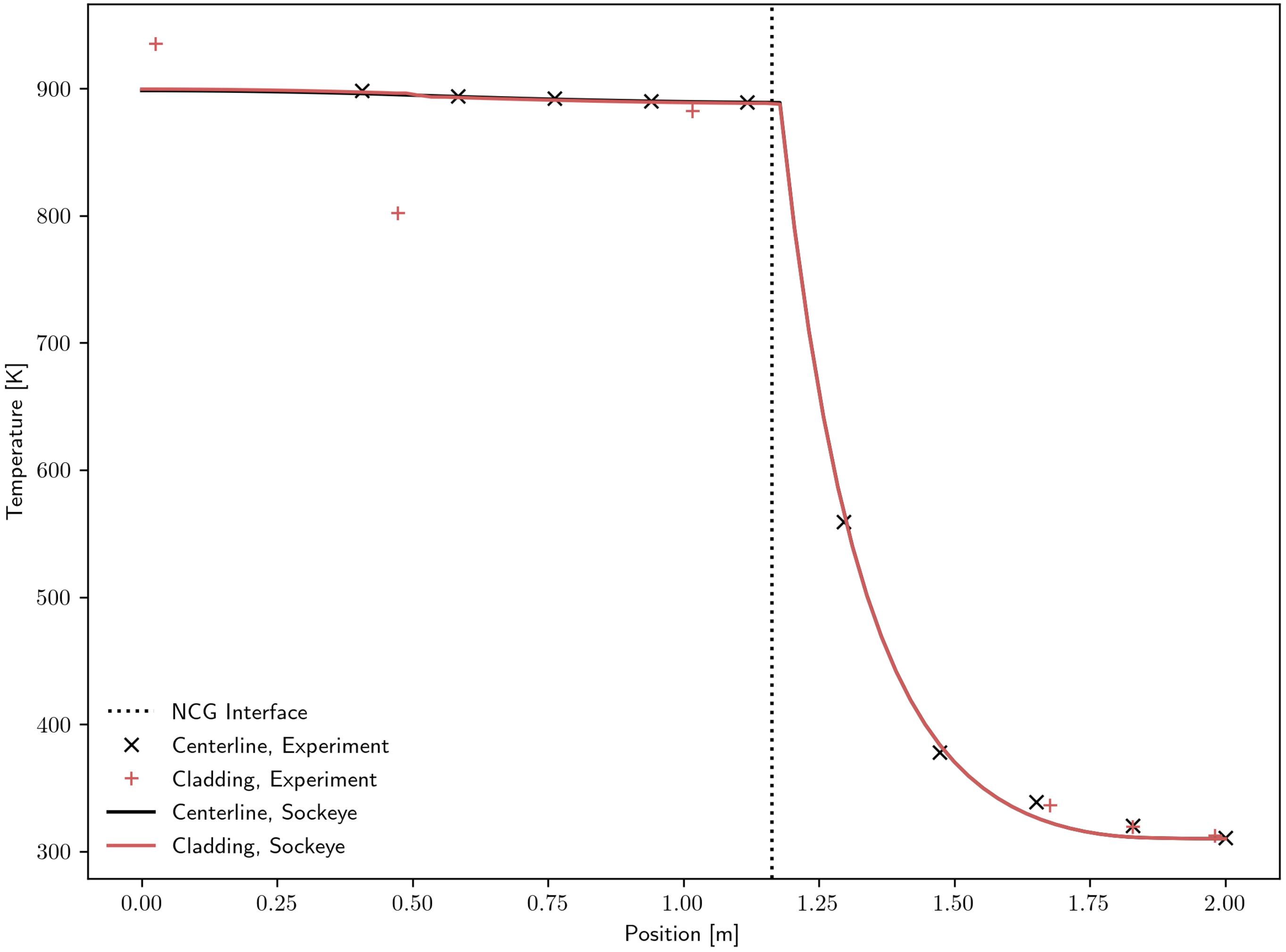


SPHERE (2021)

SPHERE: Single Primary Heat Extraction and Removal Emulator

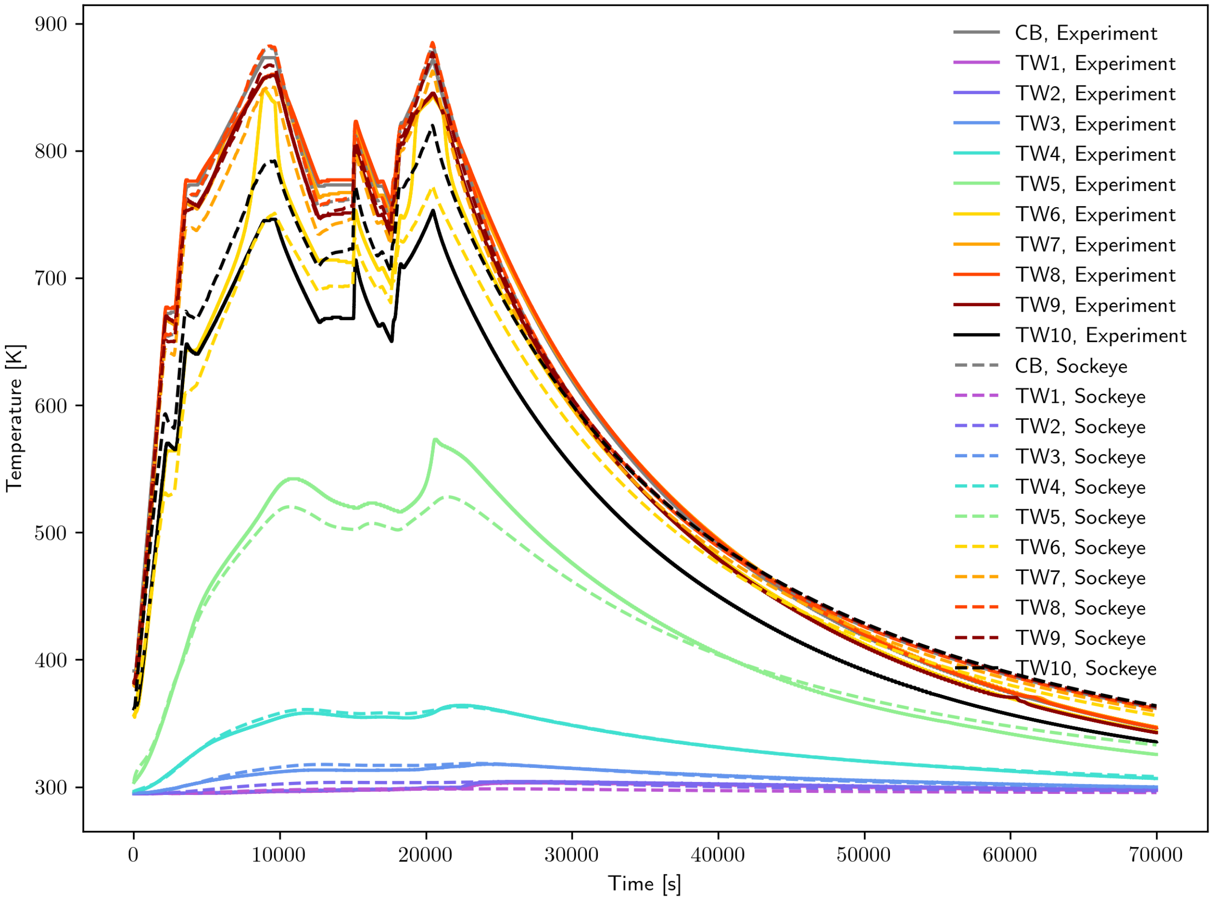


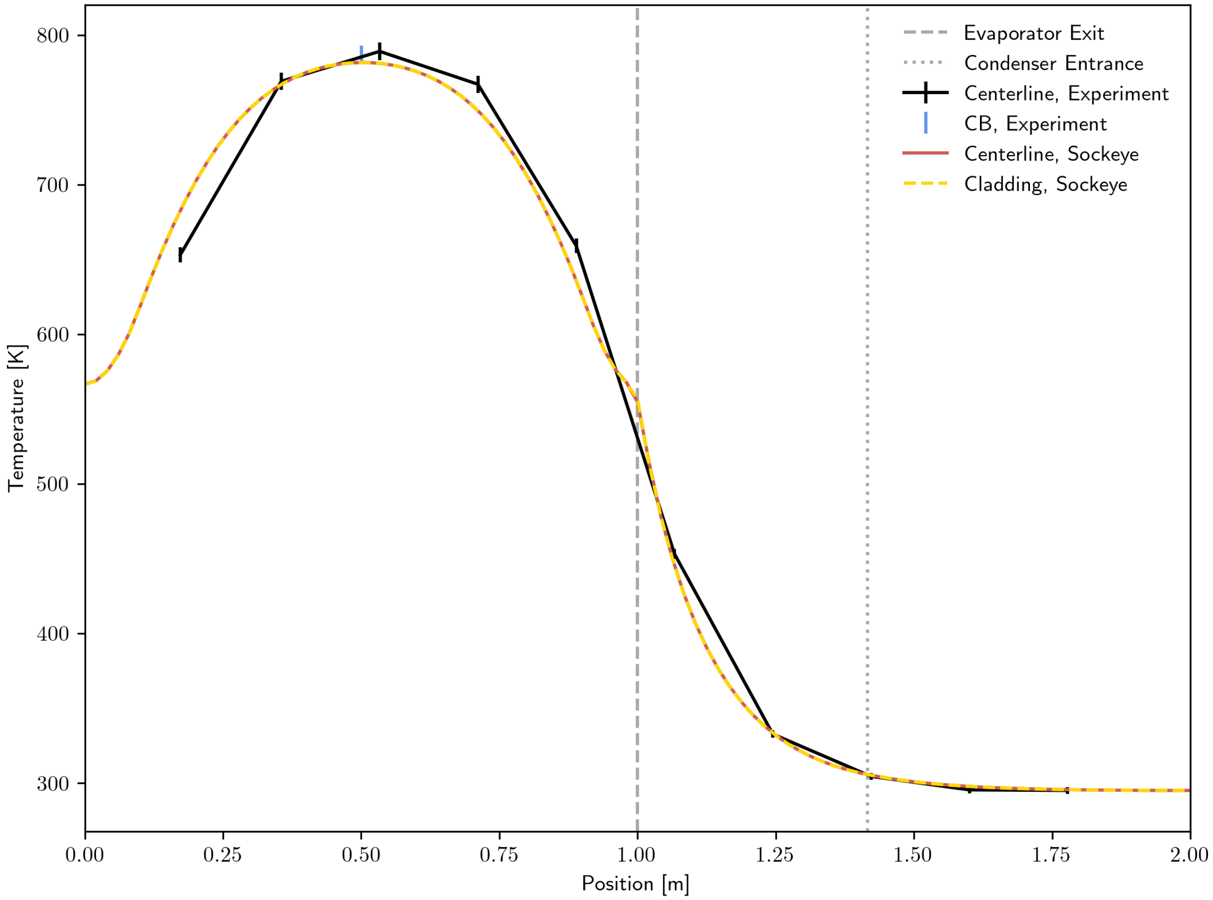




MAGNET Single-Heat-Pipe Experiment

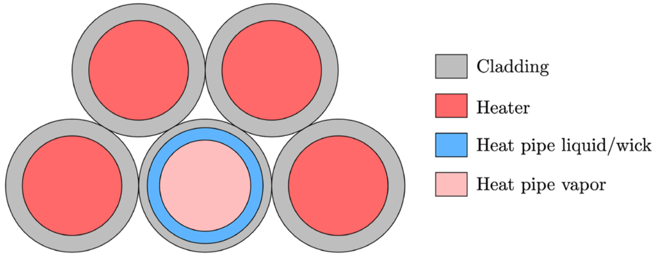
MAGNET: Microreactor AGile Non-nuclear Experimental Testbed



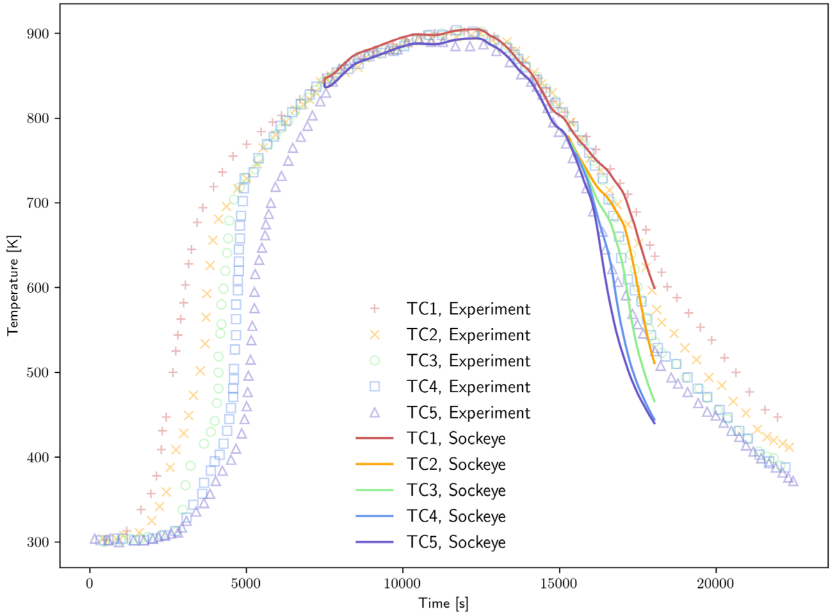


SAFE-30 Assessment

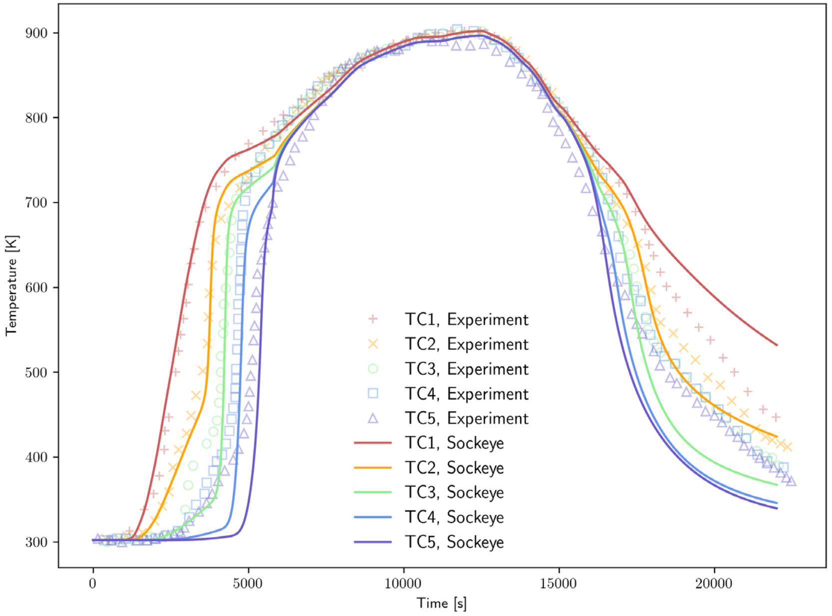
SAFE: Safe, Affordable Fission Engine



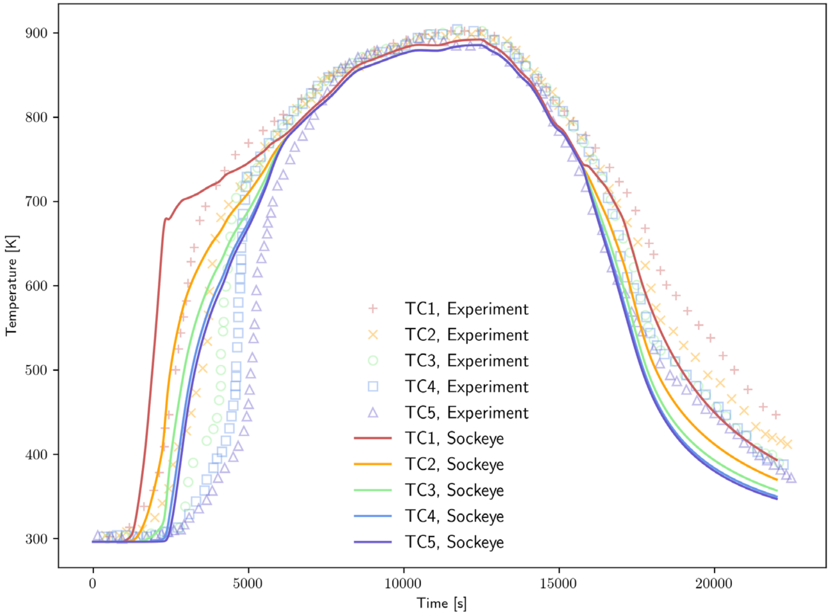
Two-Phase Flow Model



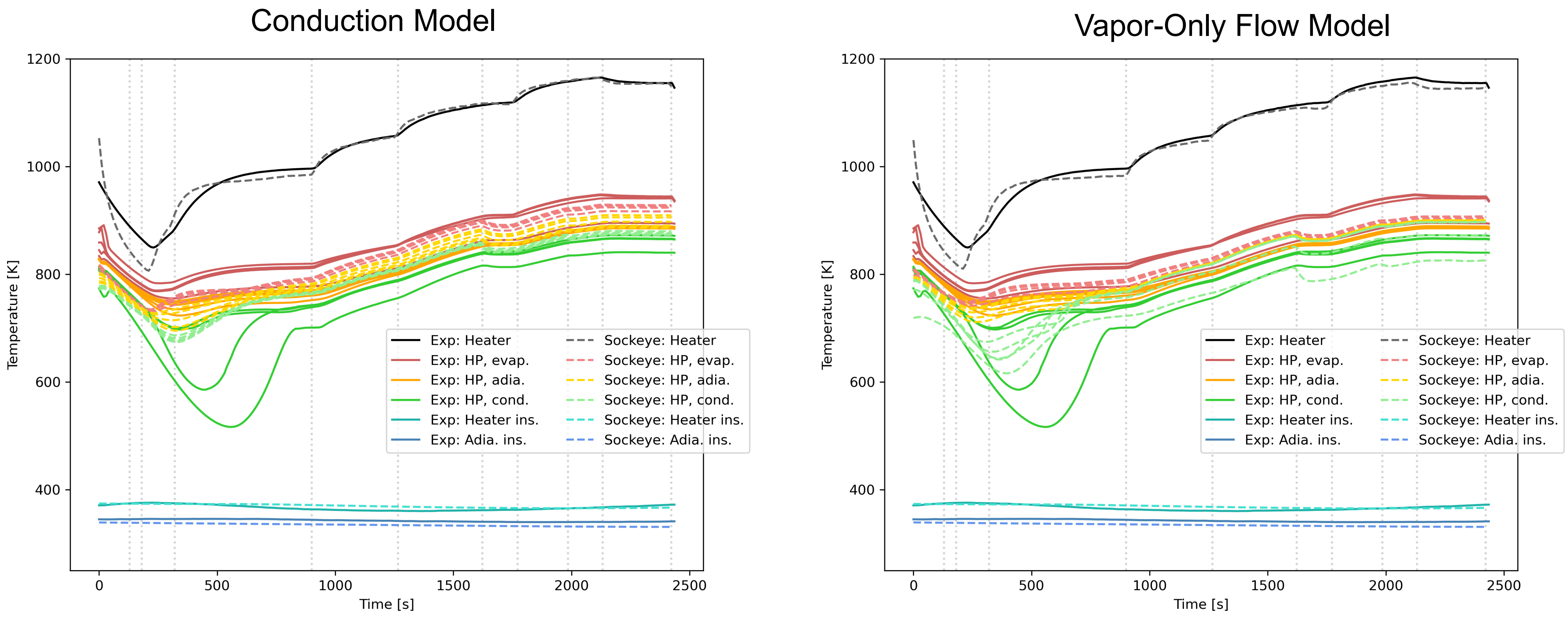
Vapor-Only Flow Model



Conduction Model



University of Michigan Experiments



Conclusions

- Validation is difficult
  - Results dominated external heat transfer
    - 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

Future Work

- Upcoming PIRT (Phenomenon Identification and Ranking Table)
- More validation
  - Long-duration testing at SPHERE (by Dec. 2024)
  - “Controlled emissivity” tests in SPHERE (Spring 2025)
- Various model refinements to the vapor-only flow model (by June 2025)
  - Startup dynamics
  - Noncondensable gas equations
- Multidimensional, multiphase flow model (beyond Fiscal Year 2025)

Idaho National Laboratory

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Applying for Sockeye

- Go to https://inl.gov/ncrc/
- Click "Make/Manage Requests"
- Make a Nuclear Computational Resource Center 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