INL/MIS-20-59624-Revision-0

# Sockeye Development and Status - August 2020

August 2020

Changing the World's Energy Future

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# Sockeye

## Development and Status

August 2020

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

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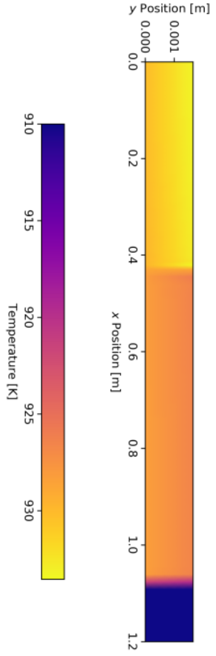
# NEAMS Heat Pipe Modeling Objectives

- **The objective of the heat pipe modeling component of NEAMS is to provide an <u>engineering tool</u> for design and safety analysis of microreactors:**
  - It must be usable within a <u>multi-physics</u> application (BlueCRAB, DireWolf);
  - It must be <u>fast-running</u> and <u>robust</u>;
  - It must allow for the <u>evaluation of transients</u> including behavior during startup and shutdown;
  - It must allow for the <u>evaluation of operational limits</u>.
- **Sockeye is the heat pipe modeling tool for the thermal-hydraulics area of NEAMS.**
  - Heat pipe modeling component of DireWolf;
  - It includes a simplified heat structure model and 1D flow model with 2D heat structures;
  - <u>*Need for closure relationships and validation for a broad range of terms in the 1D flow model.*</u>
- **SAM also includes some simplified heat pipe modeling for use in BlueCRAB.**
  - Effective conduction model;
  - Driven by NRC needs.
- **Currently we are not investing into three-dimensional CFD modeling of heat pipes.**
  - However we are performing some smaller-scale CFD simulations to address specific questions (e.g., friction models in the wick).



Sockeye result example

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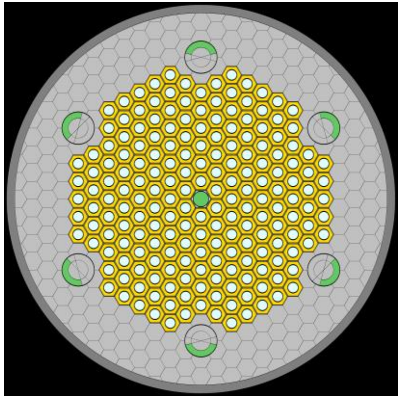
# SAM and Sockeye

Sockeye is the heat pipe modeling tool for the thermal-hydraulics area of NEAMS. SAM also includes some simplified heat pipe modeling for use in BlueCRAB.

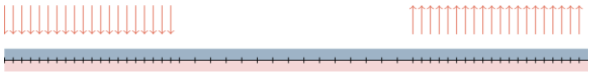
| | SAM | Sockeye |
|---|---|---|
| Simplified effective conduction model | Yes | Yes |
| 1D internal flow model (two-phase) | No | Yes |
| Transient internal flow models to address startup and shutdown | No | Yes |
| Operational limits based on correlations | Planned | Yes |
| Mechanistic operational limits based on flow models | No | Planned |



SAM has been used with a simplified effective conduction model in BlueCRAB

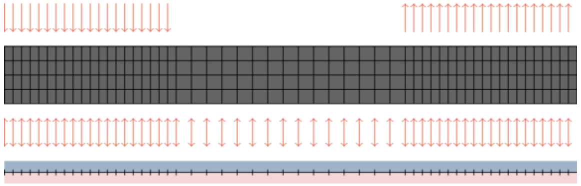
# Sockeye Simulation Capabilities

## 1D Flow



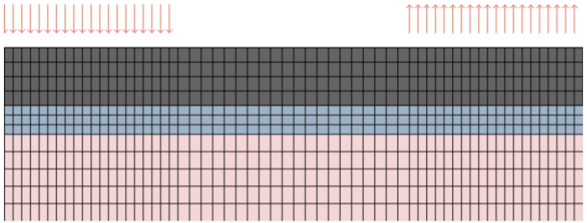
- Heat applied directly to working fluid, neglecting thermal capacity and resistance of cladding.

## 1D Flow + 2D Heat Conduction



- Heat applied to outer surface of cladding.
- Cladding exchanges heat with working fluid.

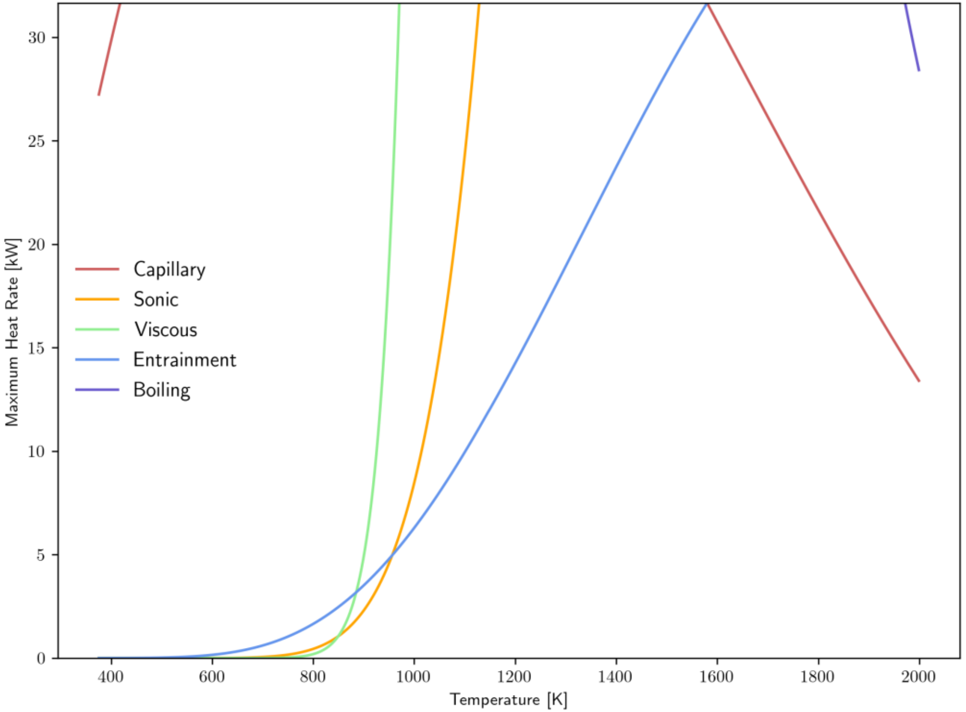
## 2D “Blackbox” Heat Conduction



- Heat applied to outer surface of cladding.
- Liquid approximated as at rest.
- Vapor approximated using high effective thermal conductivity.

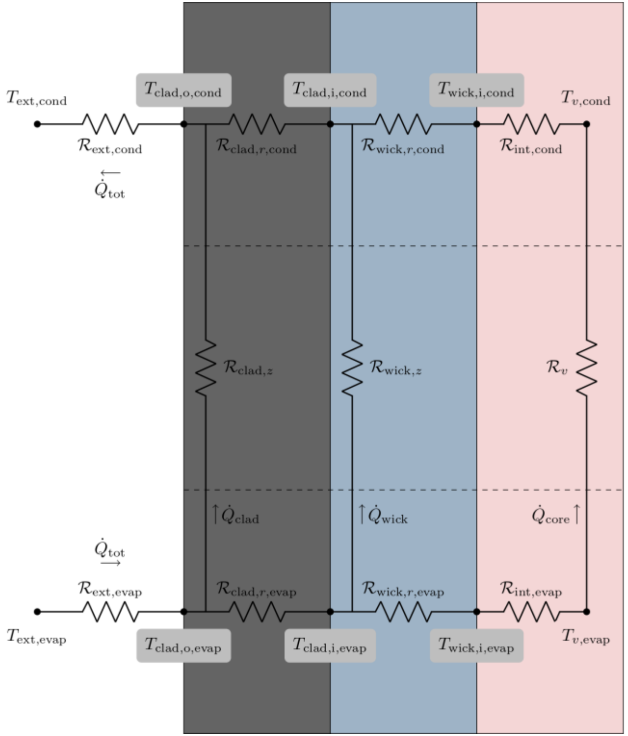
# Analytic Operational Limit Viewer

- Several heat pipe operational limits have been implemented from analytic relations.
- These are expressed in terms of heat rate vs. temperature.
- Input file provided where user edits heat pipe parameters and then runs with Sockeye.
- Plot script provided to plot the resulting operating envelope.



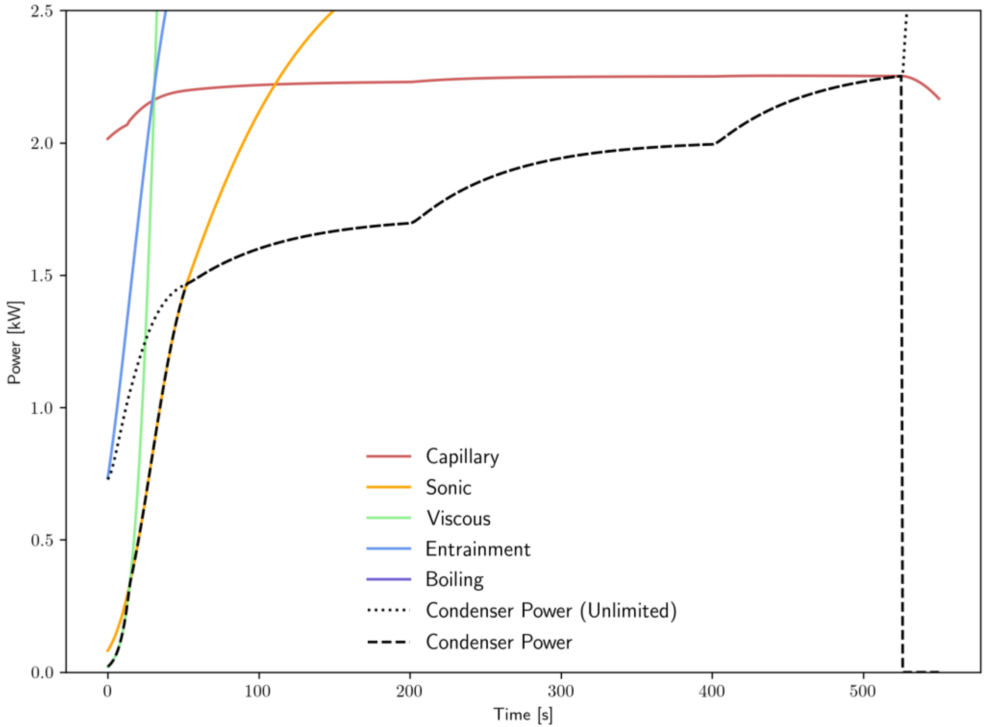
# 2D Blackbox Heat Conduction

- All radial regions of heat pipe (cladding, liquid/wick, and core) modeled with 2D heat conduction.
- Effective thermal conductivity for the liquid/wick region is used based on porosity-weighted average of constituent thermal conductivities.
- Core region gets a very high effective thermal conductivity that is based on steady-state thermal resistance analysis (see right).
- Analytic *steady-state* operational limits are optionally enforced on the boundary conditions at either end.



# 2D Blackbox Heat Conduction Example

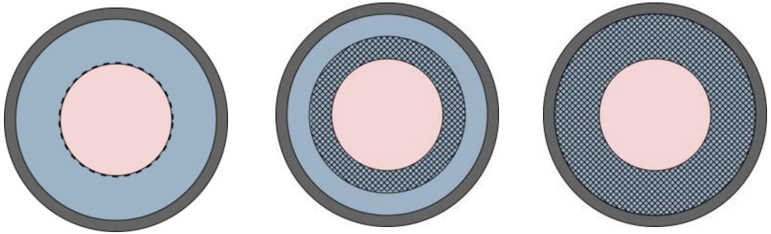
- **Cascading failure example:**
  - For 200 s, heat at rate Q.
  - At 200 s, increase heat rate by Q/6 due to failure of adjacent heat pipe.
  - At 400 s, increase heat rate by another Q/6 due to failure of another adjacent heat pipe.
- **Results:**
  - In beginning of transient, heat rate is limited by viscous and sonic limits until it heats up enough.
  - Heat pipe handles one adjacent failure, but not two - the capillary limit is reached.
  - Unlike viscous and sonic limits, capillary limit leads to dryout, making heat pipe ineffective for heat removal.



# 1D Flow

## Scope

- **Wick type is annular region of any thickness.**
  - No grooved or arterial wicks.

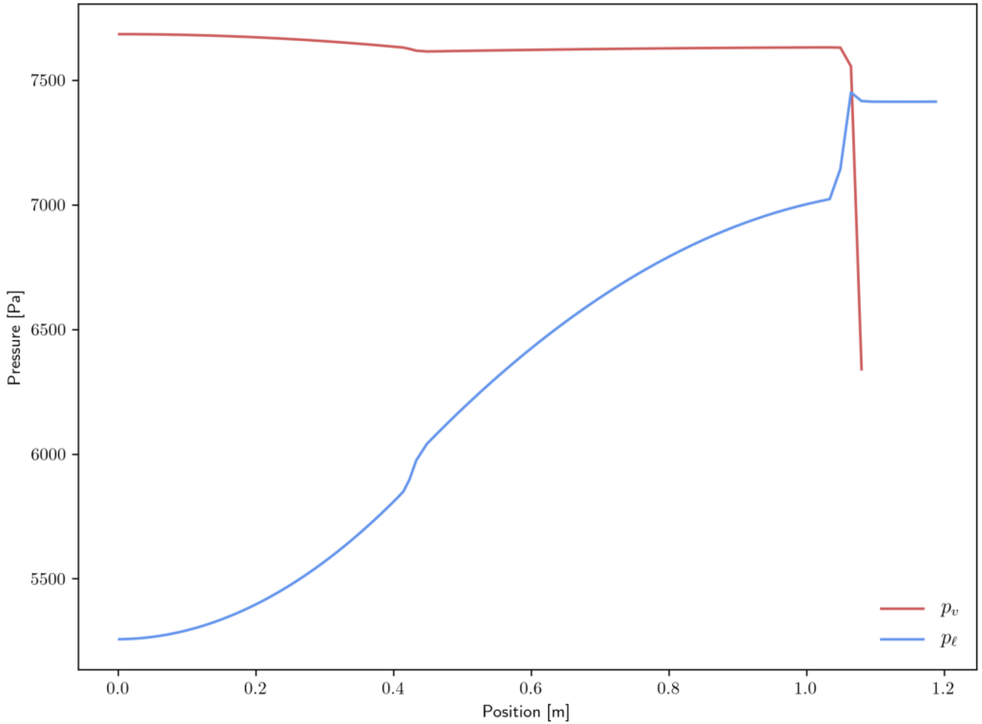


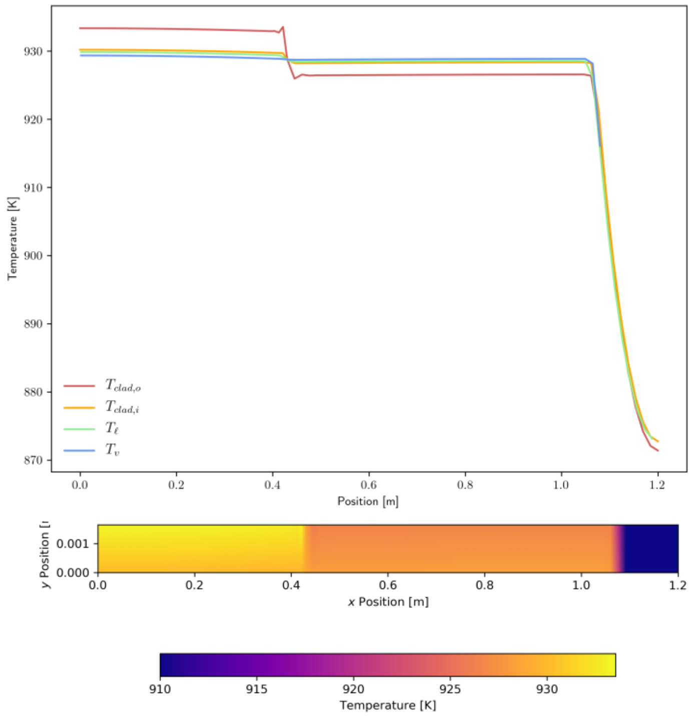
- **Available working fluids:**
  - sodium
  - potassium
- **No non-condensable gases.**

## Models

- **1D, 2-phase, compressible flow.**
- **Well-posed system of 7 PDEs:**
  - Volume fraction balance
  - Liquid/vapor mass conservation
  - Liquid/vapor momentum balance
  - Liquid/vapor energy conservation
- **Finite volume discretization.**
- **Closures:**
  - Capillary pressure
  - Interfacial area density
  - Interfacial heat transfer coefficients
  - Wall heat transfer coefficients
  - Wick permeability
  - Vapor friction
  - Interfacial friction

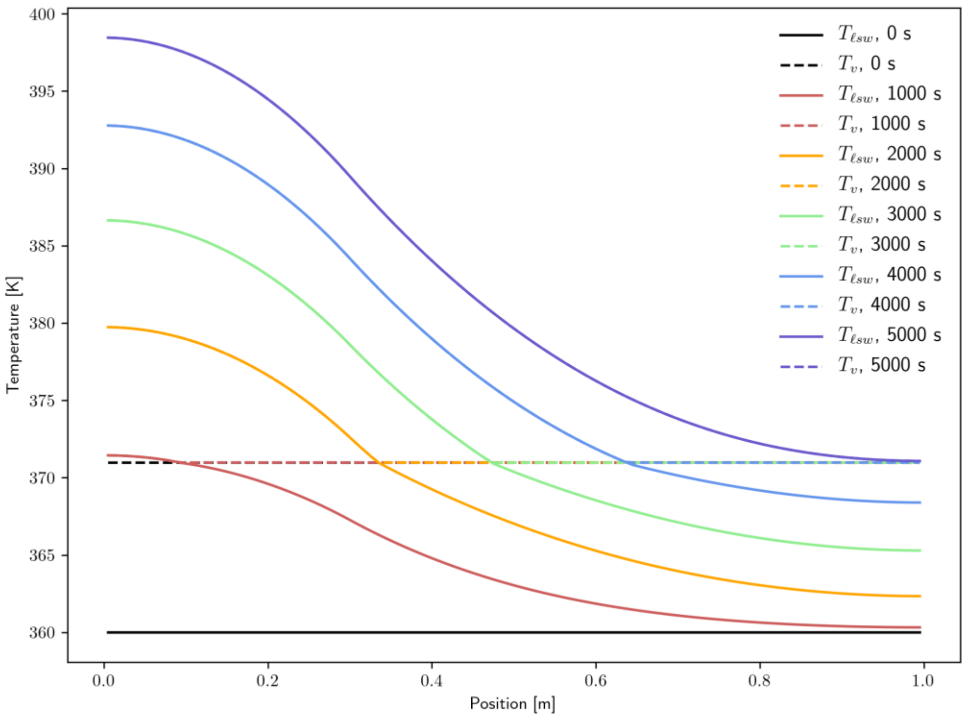
# 1D Flow + 2D Heat Conduction Example



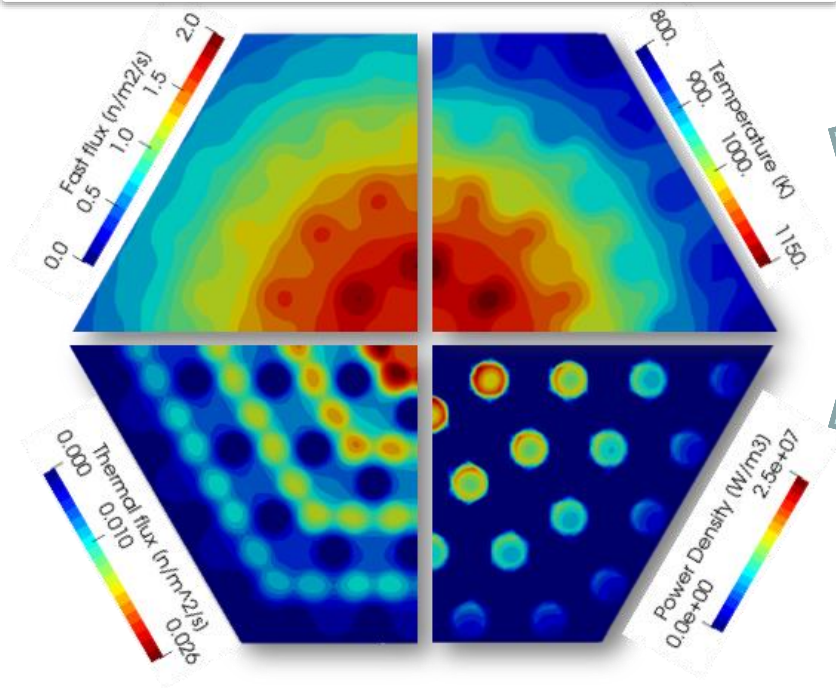
# 1D Flow Startup Modeling

- **Flow modeling during startup is challenging.**
  - Saturation pressure near the triple point is O(-5) Pa - essentially a vacuum.
    - equation of state challenges.
  - Vapor starts in rarefied gas regime, not continuum regime, until a continuum builds and moves down the heat pipe.
  - Complex fluid-solid interactions during melting.
  - Large temperature gradient.
- **Melt capability was recently added but is not robust.**
  - If not heated uniformly, must be heated very slowly - example to the right heated at 1 W.

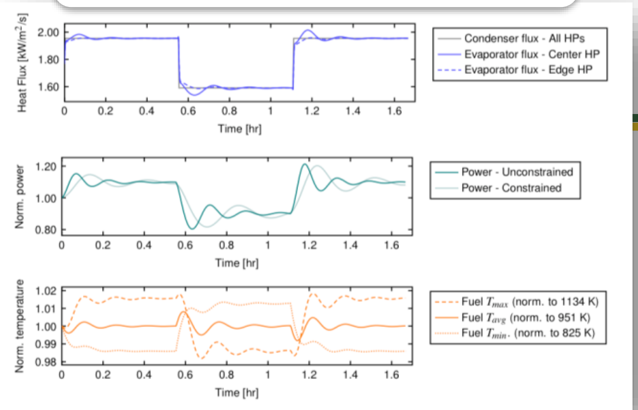


# Multi-physics Coupling

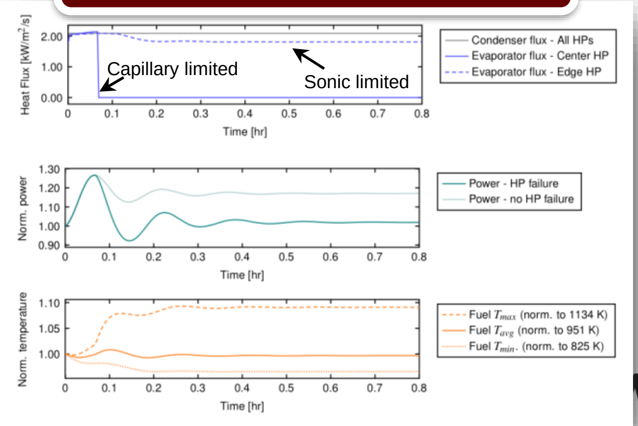
Leverage DireWolf coupled simulations started under ARPA-E MEITNER




## Power Transients




## Cascading HP Failure

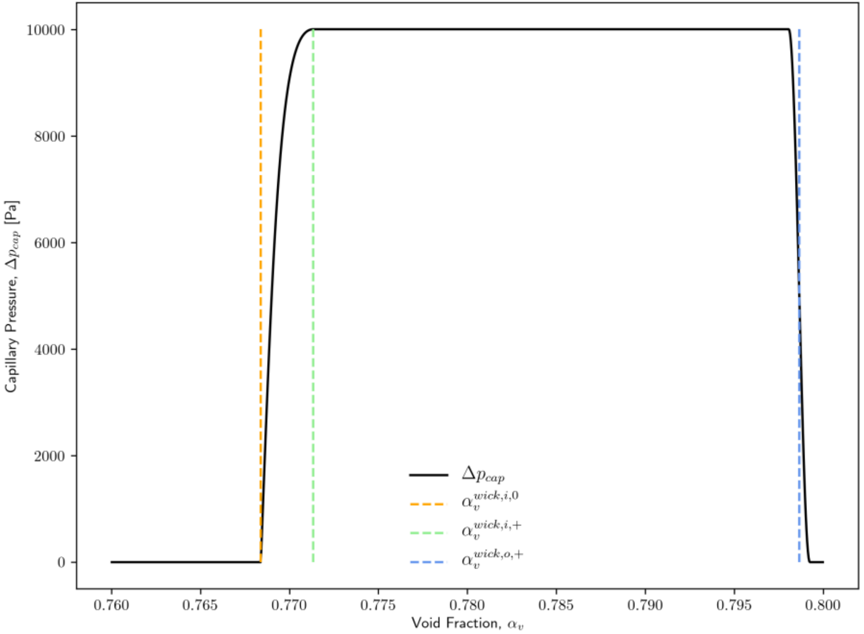


# Planned Future Development

- **1D Flow model improvements:**
  - Add models for entrainment limit and boiling limit.
  - Increase robustness for phase disappearance (dryout and liquid pools).
  - Add wetting/de-wetting terms.
  - Refine capillary pressure model.
  - Increase robustness of startup.
- **2D Blackbox model improvements:**
  - Add melt/startup capability.
  - Refine effective thermal conductivities.

# 1D Flow Closures: Capillary Pressure

- **Capillary pressure is used in pressure relaxation terms.**
  - Phases expand/contract to try to accommodate the condition $\Delta p_{cap} = p_v - p_l$.
- **The void fraction solution $\alpha_v$ is used to estimate the curvature of the liquid-vapor interface using geometrical wick parameters and assumption of spherical pores.**
- **ANL team found data indicating saturation-dependence of capillary pressure with the interface inside the wick.**
  - Currently have assumed constant capillary pressure within the wick, as shown on right.



# 1D Flow Closures: Interfacial Area Density

- **Interfacial area density: the area per unit volume of the liquid-vapor interface.**
  - Some interfacial interaction terms are proportional to this quantity:
    - Interfacial heat and mass transfer
    - Pressure relaxation rate
- **Like capillary pressure, its currently relation in Sockeye is based on the void fraction and assumed liquid-vapor interface geometries in different regimes:**
  - Within wick, curved interface in each pore.
  - Outside wick, flat interface.

# 1D Flow Closures: Interfacial Heat Transfer Coefficients

- **Interfacial heat transfer is directly related to evaporation/condensation rates in Sockeye:**
  - An interface temperature is computed, and each phase performs convective heat transfer with this interface temperature.
  - The net heat transfer to the interface (along with latent heat) determines the mass flux between phases:

$$\Gamma_{l\to v} = \frac{\mathcal{H}_l^{int}(T_l - T_{int}) - \mathcal{H}_v^{int}(T_v - T_{int})}{h_{lv}}$$

- **Sockeye needs closures for the interfacial heat transfer coefficients $\mathcal{H}_l^{int}$ and $\mathcal{H}_v^{int}$.**
  - We know that these are “large” values from thermal resistance analysis, but don’t know much more than this.
  - Currently these are given by the user as constants.

# 1D Flow Closures: Needs Summary

- **Capillary pressure profile may need modification:**
  - Wick saturation dependence.
  - Curvature reversal (thus leading to negative capillary pressure).
  - Hysteresis effects (dependency on direction of interface movement).
  - Contact angle temperature dependence.
- **Interfacial heat transfer coefficients need a closure.**
  - Currently they are just user-input “large” values.
- **Interfacial friction factors need a closure.**
  - Currently interfacial friction is neglected.
- **Wall heat transfer coefficients have a closure but need validation.**
- **Vapor friction factor has a closure but needs validation.**
- **Liquid pressure drop needs validation:**
  - Assumed due only to porous flow through wick.
  - Wall friction neglected due to low speed.

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# Closures Development Example Using Nek5000

- **Nek5000 used to compute friction factors in vapor core and liquid annulus/gap.**
  - Used porous media model to account for wick.
  - Varied two parameters:
    - Liquid-vapor interface location within the wick, corresponding to some volume fraction
    - Wick permeability
  - Friction factors normalized to values for single-phase flow in a pipe/annulus.
  - Power law fits used to preserve limiting behavior at zero permeability.
- **Results on right for single volume fraction:**
  - Liquid annulus/gap: increased flow area from the wick acts to reduce the overall pressure drop.
  - Vapor core: wick acts as surface roughness, increasing overall pressure drop.