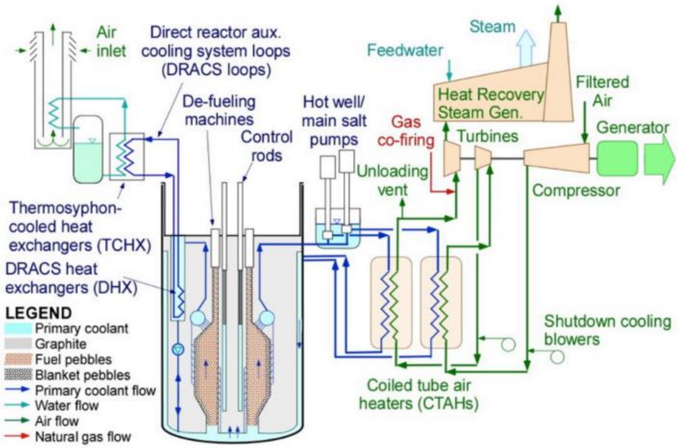
DEPARTMENT OF
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Benchmark Simulation of Natural Circulation Cooling Systems with Salt Working Fluid Using SAM



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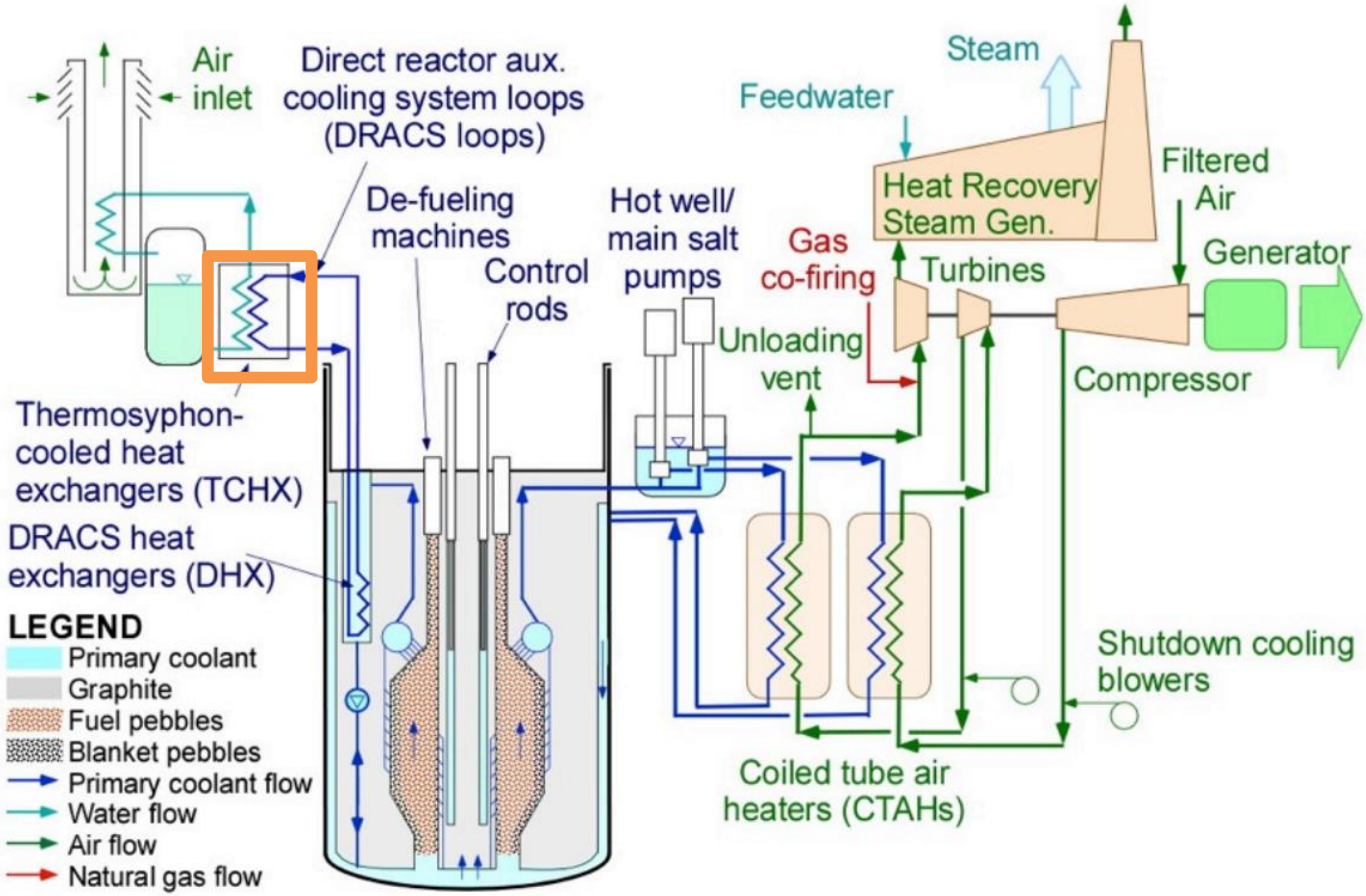
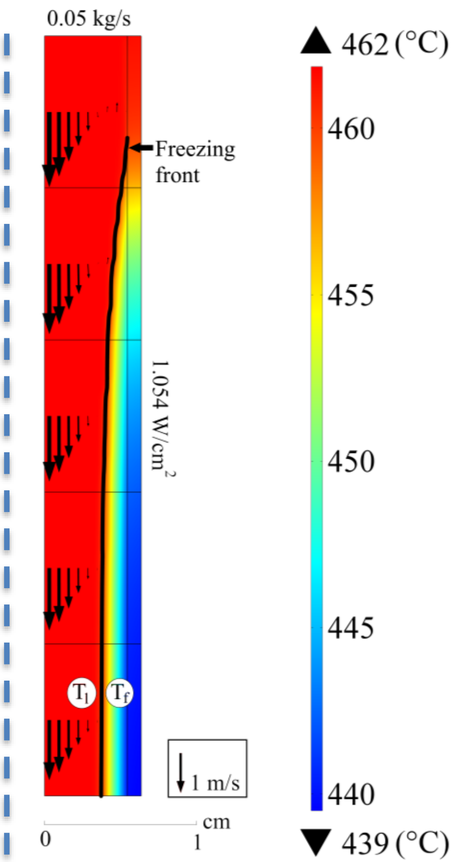
17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17)
9-7-2017
Xi’an, China

Background and Motivation



"Mark 1" Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor

Pipe Freezing Simulation



Physics: Radiative heat transfer, bouyancy force, axisymmertic

Outline

- Intro: system code analysis for salt-cooled and molten-salt reactors
- Description of System Analysis Module (SAM)
- Case Study: PB-FHR
    - Pebble-bed Fluoride salt-cooled High-temperature Reactor
    - Salt properties
    - Secondary loop model
    - Primary loop model
        - Heat structures, core pressure loss, pump coastdown
    - Transient scenario results and discussion
- Path forward and related work

System Analysis Module (SAM)

- Plant-level system tool for transient scenario safety analysis
- Built on MOOSE (finite element framework)
  - High-order FEM for fluid flow and heat transfer
- Incompressible, thermally expandable flow
  - Inherent buoyancy-driven circulation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial z} = 0 ,$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u + p)}{\partial z} = -\rho g - \frac{f}{D_e}\frac{\rho u|u|}{2} ,$$

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial(\rho u H)}{\partial z} = q''' ,$$

Argonne NATIONAL LABORATORY

DR. RUI HU (Lead Developer)
Principal Nuclear Engineer
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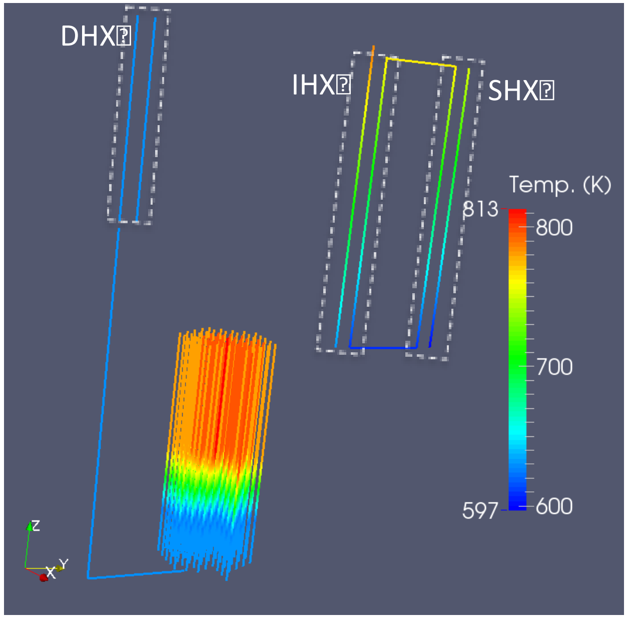
System Analysis Module (SAM)

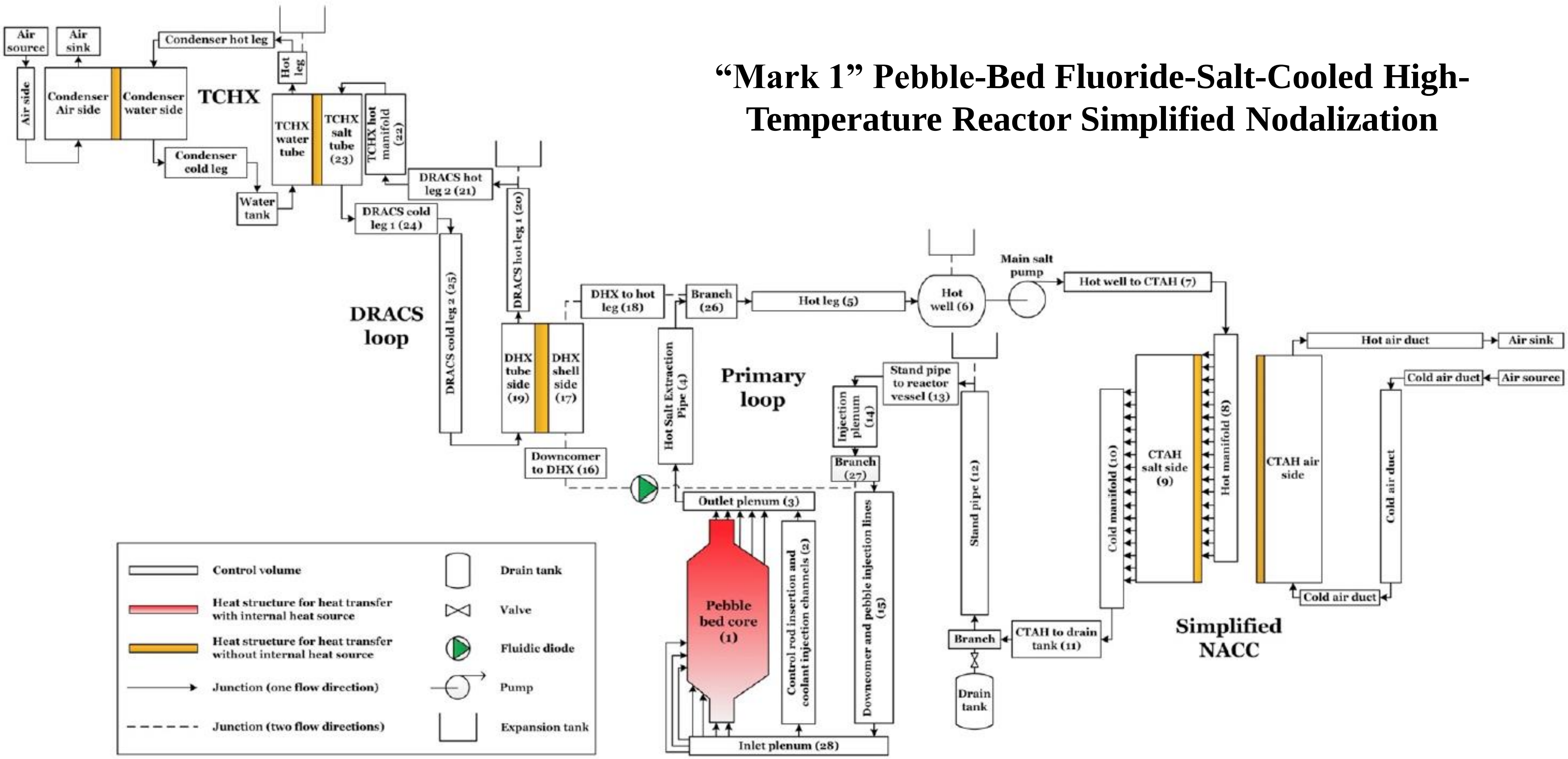
- Modular, component based development
- Flexible for multi-scale modeling
  - STAR-CCM+, SHARP, SAS4A/SASSYS-1 …
- Single or multi-channel core models
  - Flexible full-core modeling
- QA and V&V approach used by MOOSE
  - Development with version control, unit testing, etc.
  - Verification with analytical benchmarks, code-to-code comparison
  - Validation matrix in progress: EBR-II, FFTF, etc.
- Projects to enhance SAM for MSR/FHR modeling



Simulation of ABTR PLOF

Case Study: Mk1 PB-FHR Model

“Mark 1” Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor Simplified Nodalization



Challenge: recreate RELAP5-3D model, address discrepancies

Building Mk1 PBFHR: Properties

- Molten salt properties were initially implemented differently
- For purpose of comparison, RELAP5 (R5) version implemented in SAM
- Note: most significant effect is from thermal conductivity *k*
  - $h = Nu * \frac{k}{L}$

FLiBe property	SAM Default (T in C, SI units) [3]	@700 ° C	RELAP5, SAM updated (T in C, SI units) [4]	@700 ° C
Density (kg/m³)	$2279.92 - 0.488T$	1938.32	$2279.7 - 0.4884T$	1937.82
Conductivity(W/m·K)	$0.7662 + 0.0005T$	1.1162	1.1	1.1
Specific heat (J/kg·K)	2415.78	2415.78	2386	2386
Viscosity (Pa·s)	$4.638 * 10^5 * T^{-2.79}$	0.005352	$1.16 * 10^{-4} * e^{\frac{3755}{T+273.15}}$	0.005498

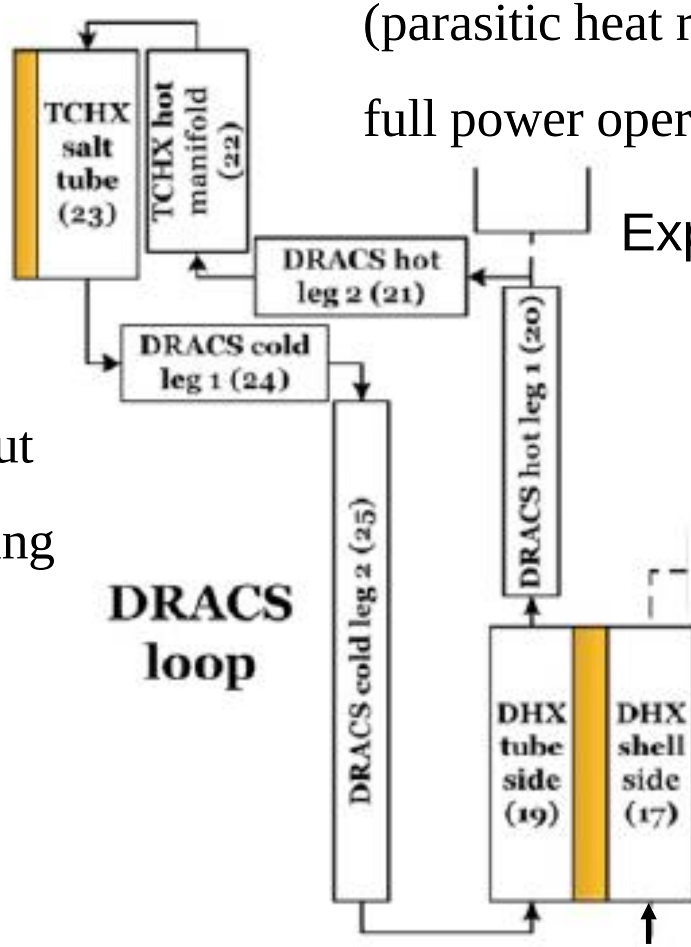
Building Mk1 PBFHR: DRACS

- Direct Reactor Auxiliary Cooling System: evaluate steady state performance

(parasitic heat removal during

full power operation of reactor)

Pipe with constant outer wall temperature, code-determined h at inner boundary with salt



Expansion tank

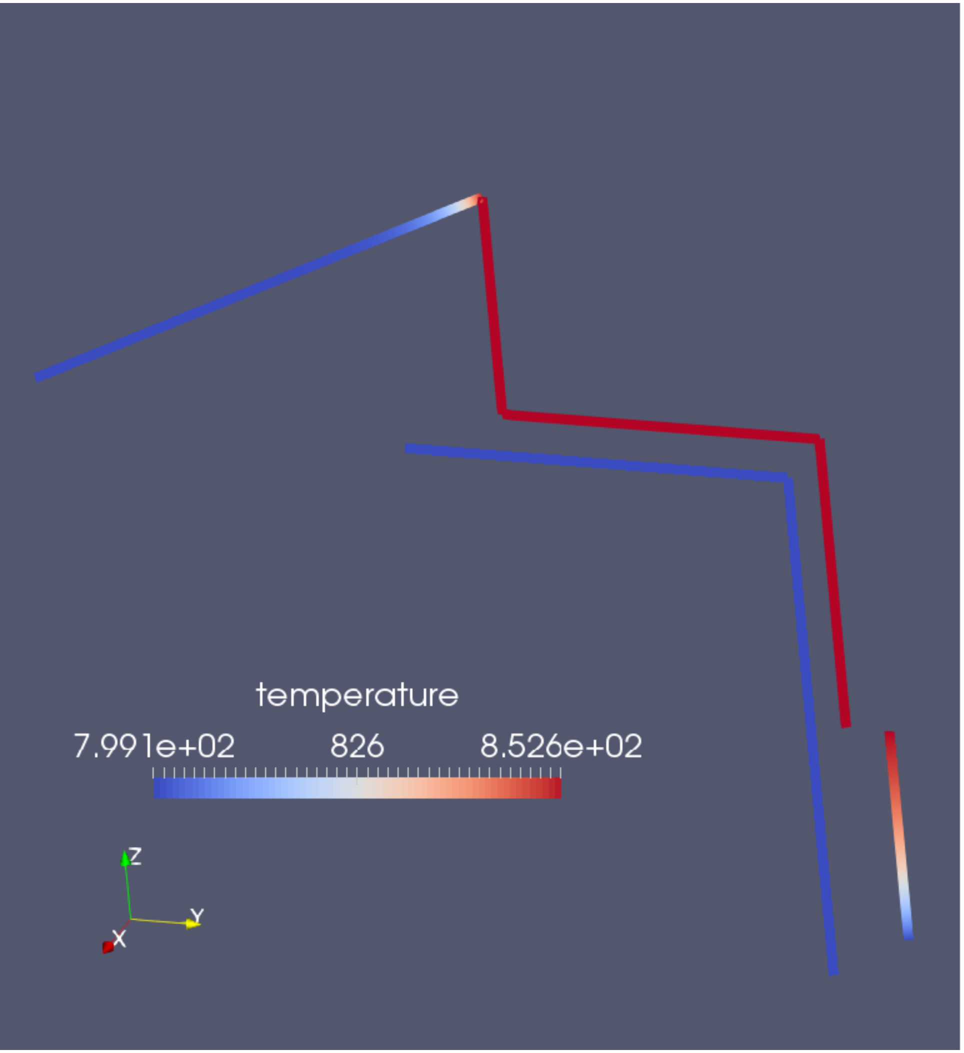
Outlet

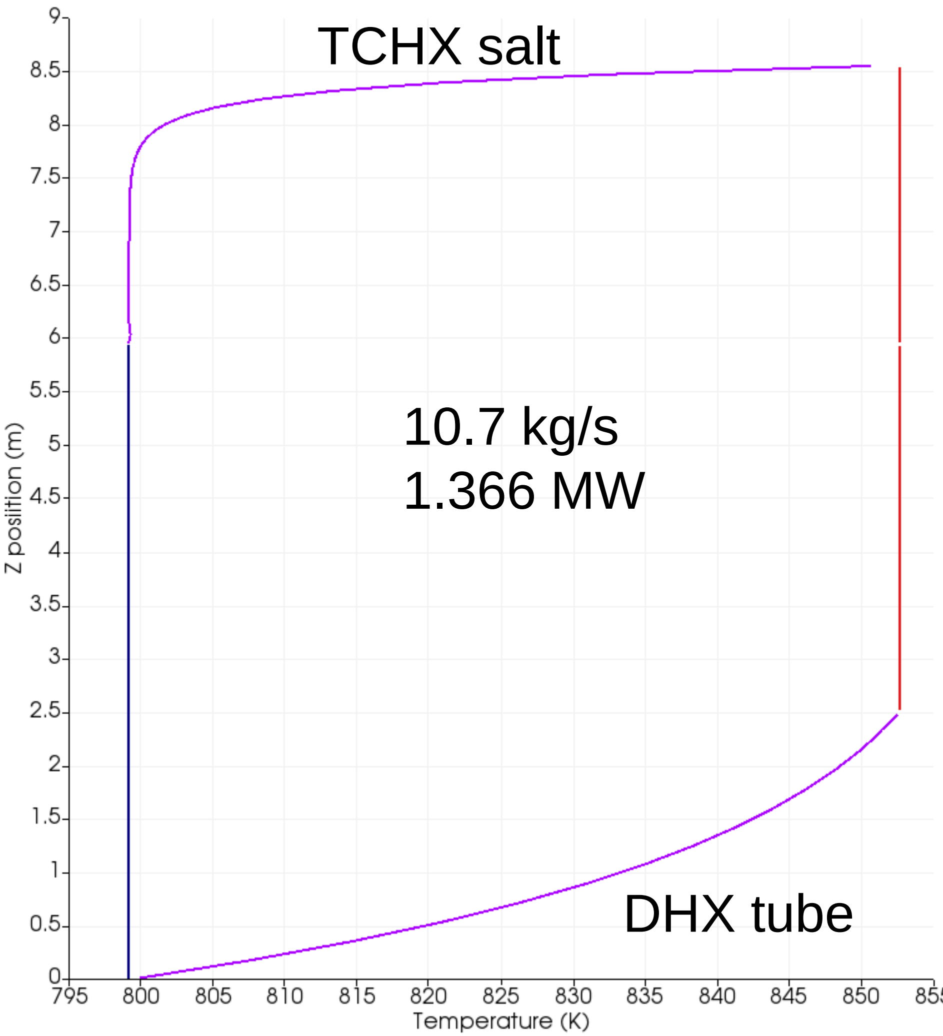
Fix salt flow rate and temperature at DHX shell inlet

Inlet

- Verify this section is input correctly before continuing
- Correct mass flow (after some tuning):
- 10.7 kg/s

DRACS Parasitic Heat Removal





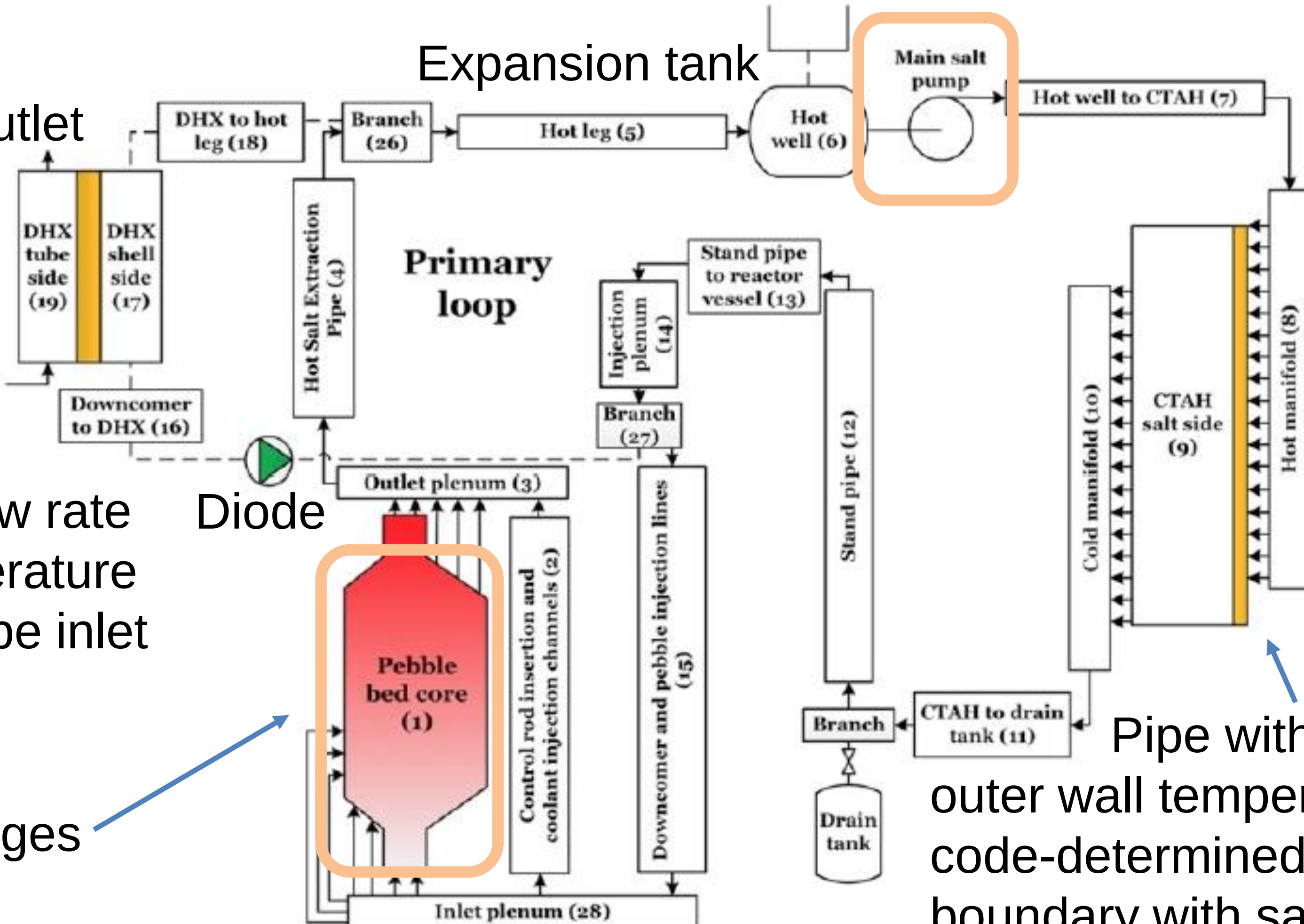
Building Mk1 PBFHR: Primary Side

- Same concept as building just the DRACS loop

Expansion tank

Outlet

Inlet



Fix salt flow rate and temperature at DHX tube inlet

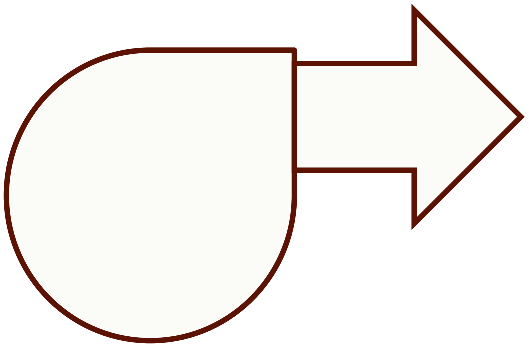
Diode

Challenges

Pipe with constant outer wall temperature, code-determined h at inner boundary with salt

Building Mk1 PBFHR: Pump Model

- Pump provided to RELAP as a simple velocity constraint
- SAM: Not possible
- Must specify a head curve

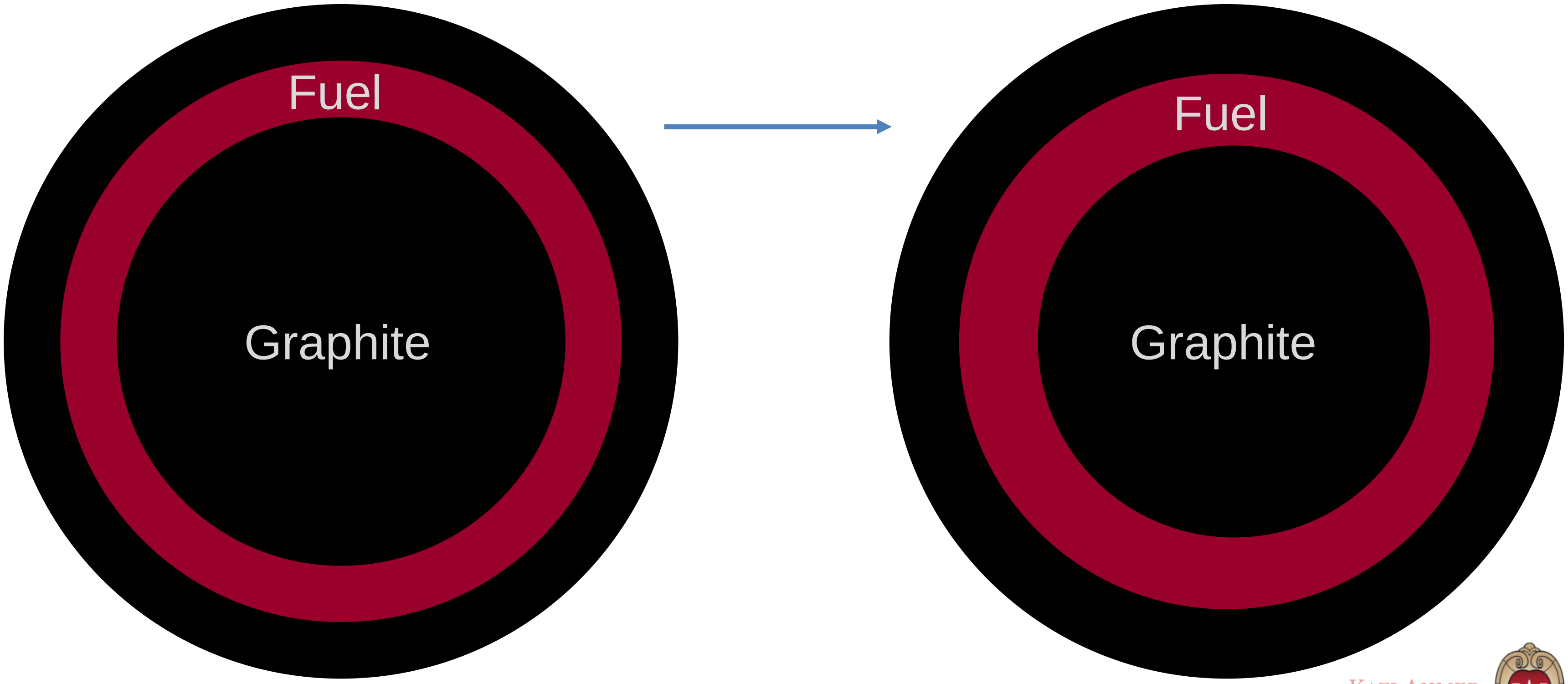


v(t) = v (piecewise linear)

- The piecewise linear velocity coastdown could be mimicked by a piecewise linear head curve
- Also require primary velocity to go to zero during transient for comparison

Building Mk1 PBFHR: Core Heat Structures

- No spherical heat structures yet in SAM
- Convert to cylindrical
- For best approximation, preserve total volume of core materials

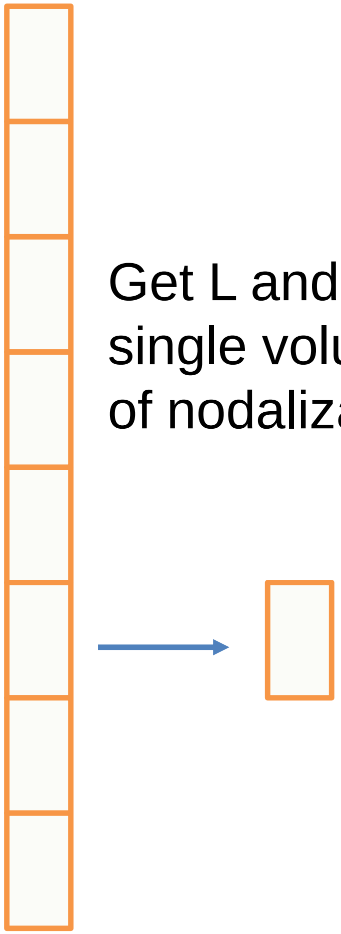


Building Mk1 PBFHR: Core Friction

- RELAP Provided values for A, B, C:
  - 32.1, 4974.4, -1.0
  - Not correct for SAM, compare codes
- Different implementation between codes
  - Multiply by D/L, new A, B, C:
  - 5.467, 847.17, -1.0
- Flow rates by component predicted by SAM:

Component	RELAP flow (kg/s)	Loss coefficient	SAM flow (kg/s)	Tuned loss coefficient	Tuned SAM flow (kg/s)
Core	771.40	(Eq. 4)	773.40	(Eq. 4)	771.38
Bypass	261.47	0.3750	263.73	0.6	261.47
Diode	51.60	100	50.78	94.5	51.62
Pump	1084.47	0	1087.92	0	1084.48

$$K + f\frac{L}{D} = A + B\mathrm{Re}^{-C}$$



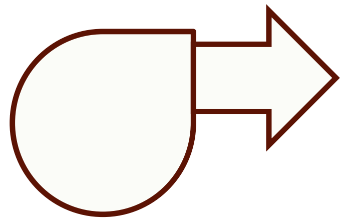
Get L and D for single volume of nodalization

Building Mk1 PBFHR: Other input

Diode: pump with 0 head

Different loss coefficient

for forward/reverse flow

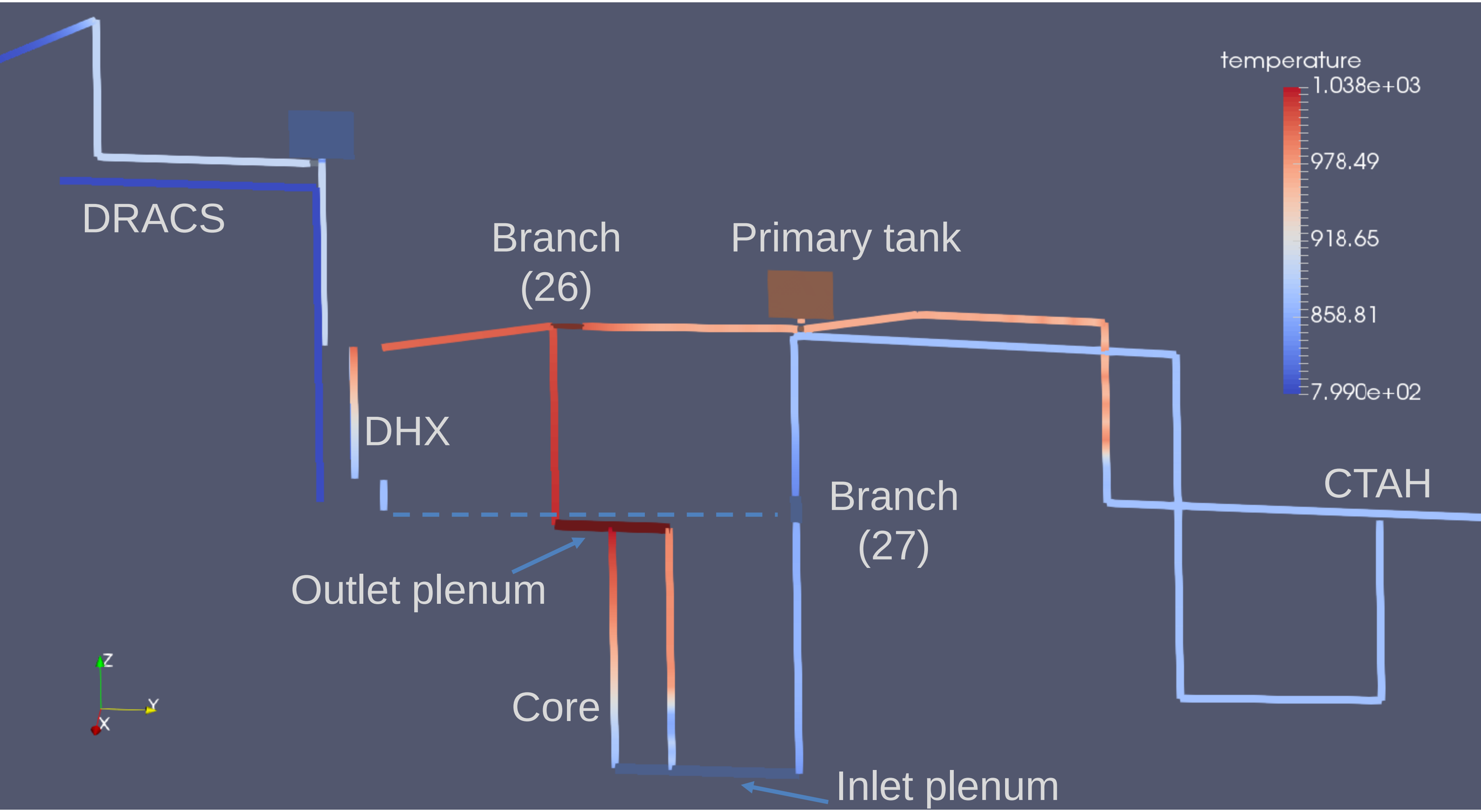


```
[./Paxial]
  type = PiecewiseConstant
  axis = 0
  direction = right
  xy_data =
        '0.176153846153846   0.0939862040
         0.352307692307692   0.2648701900
         0.528461538461539   0.4186657800
         0.704615384615385   0.5895497920
         0.880769230769231   0.7689779760
         1.056923076923080   0.9056851700
         1.233076923076920   0.9825829780
         1.409230769230770   1.0082155720
         1.585384615384620   1.0167597700
         1.761538461538460   1.0167597700
         1.937692307692310   1.0509365880
         2.113846153846150   1.1363785680
         2.290000000000000   1.2047321780
         2.466153846153850   1.2218205740
         2.642307692307690   1.2303647720
         2.818461538461540   1.2559973660
         2.994615384615380   1.2389089700
         3.170769230769230   1.1961879800
         3.346923076923080   1.1278343700
         3.523076923076920   1.0509365880
         3.699230769230770   1.0851133800
         3.875384615384620   1.1192901720
         4.051538461538460   1.1876437820
         4.227692307692310   1.2645415640
         4.403846153846150   1.3499835700
         4.580000000000000   1.2132763760'
```

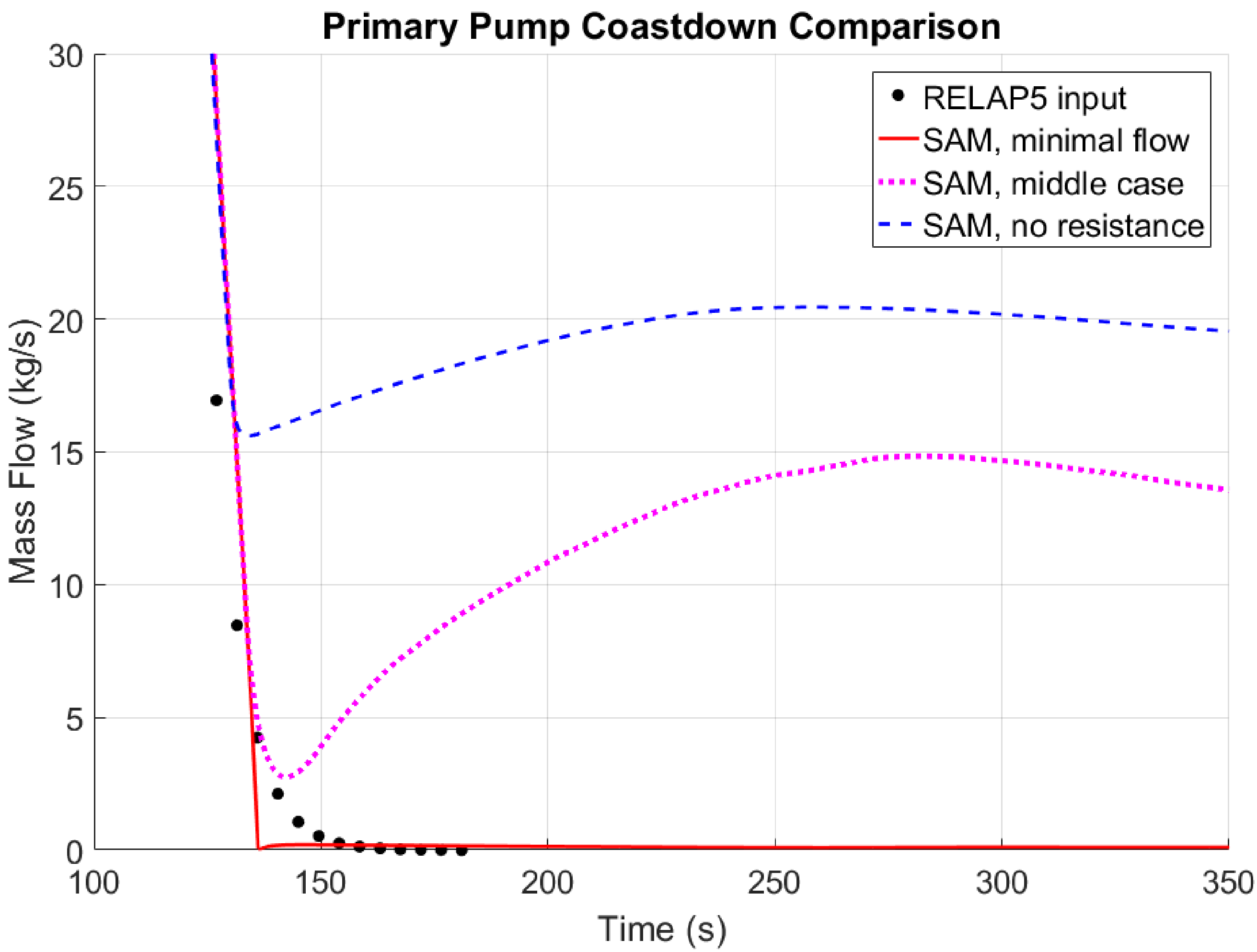
```
  [./Phead]
    type = PiecewiseLinear
x =  '0        1000      1004.5    1009      1013.5    1018      1022.5
      1027     1031.5    1036      1040.5    1045      1049.5    1054
      1058.5   1063      1067.5    1072      1076.5    1081      10000'
y =  '367475   367475    182810.4  89968.8   43302.0   19845.0   8054.3
      2127.7   -851.3    -2348.7   -3101.3   -3479.6   -3669.8   -3765.4
      -3813.4  -3837.6   -3849.7   -3855.8   -3858.9   -3860.4   -3861.9'
  [../]

  [./Phead2]
    type = PiecewiseLinear
    x = '0 100 104.5 109 113.5 118 122.5 127 10000'
    y = '367475 367475 171250 80450 38750 18600 4900 0 0'
  [../]

  [./Phead3]
    type = ParsedFunction
    #value = min(367475,371377*exp(-0.1528583*(min(t,200)-100))-3862)
    value = min(367475,371377*exp(-0.1528583*(min(t,1100)-1000))-3862)
  [../]
```

```
  [./shutdownPower]
    type = PiecewiseLinear
    x = '0     1000 1001 1002 1004 1008 1016 1024 1032 1040 1048 1060 1120 1240 1480 1960 2440 2920 3400 3880
4360 4600 13200'
    y = '1.0000000000     1.0000000000    0.0529661017    0.0508474576    0.0478813559    0.0440677966
0.0402966102    0.0378389831    0.0360593220    0.0347033898    0.0335593220    0.0321610169    0.0279237288
0.0242372881    0.0210169492    0.0179237288    0.0161016949    0.0147881356    0.0137711864    0.0130084746
0.0123728814    0.0120762712    0.0081355932'
  [../]
```

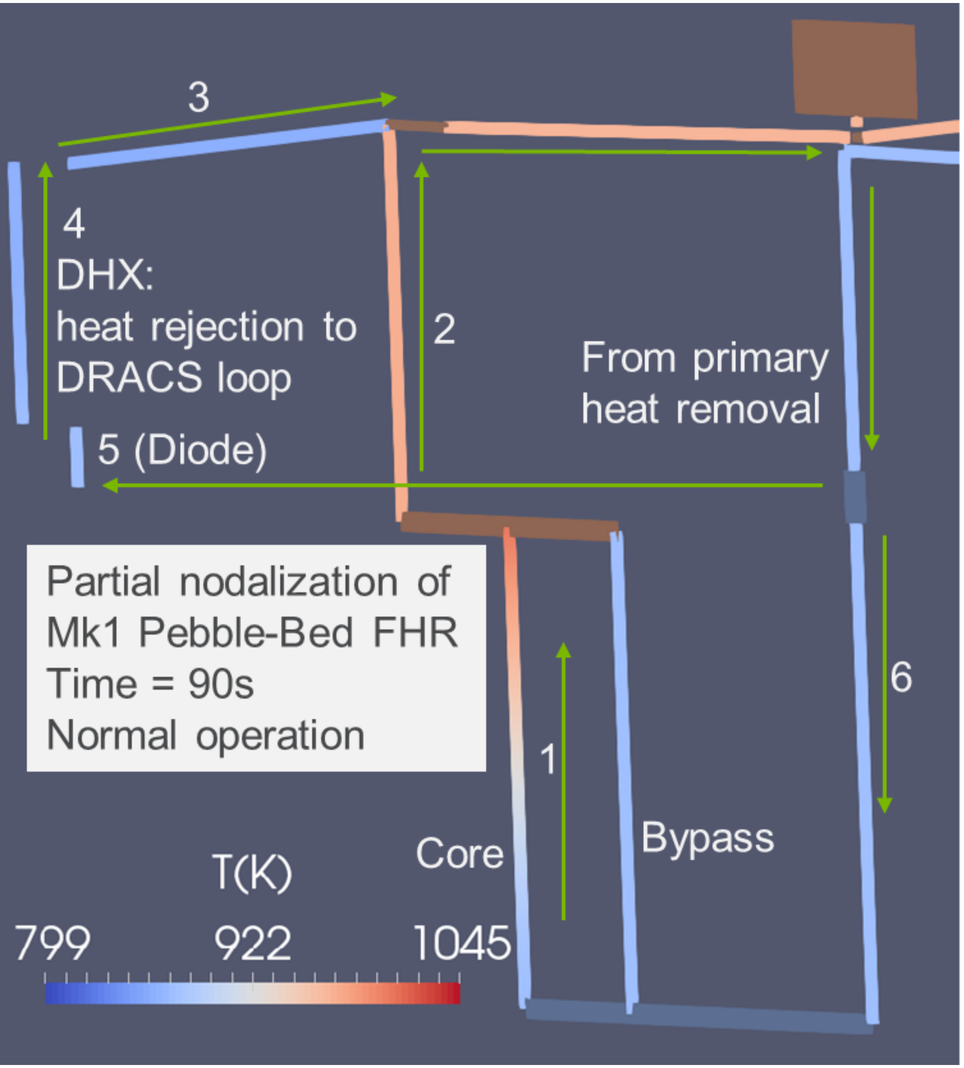
Building Mk1 PBFHR: Full Model and Transient

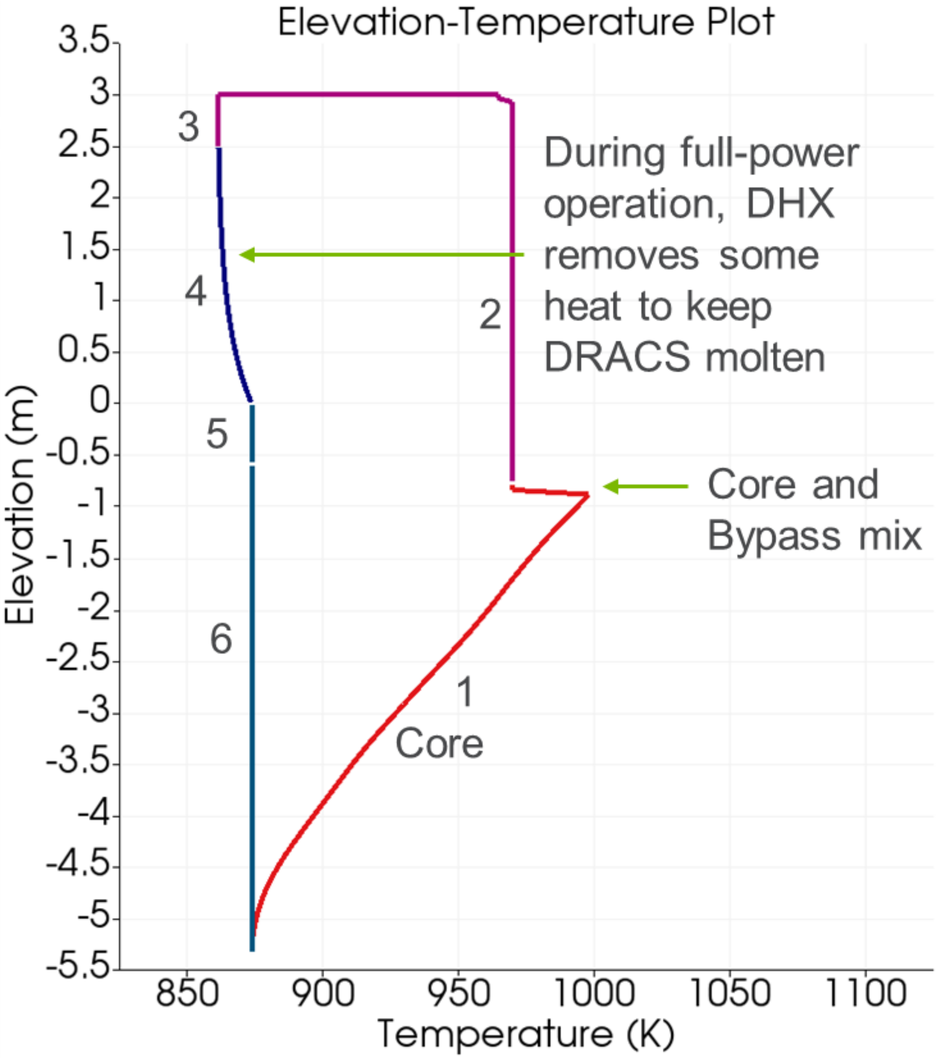


Building Mk1 PBFHR: Primary Loop Flow

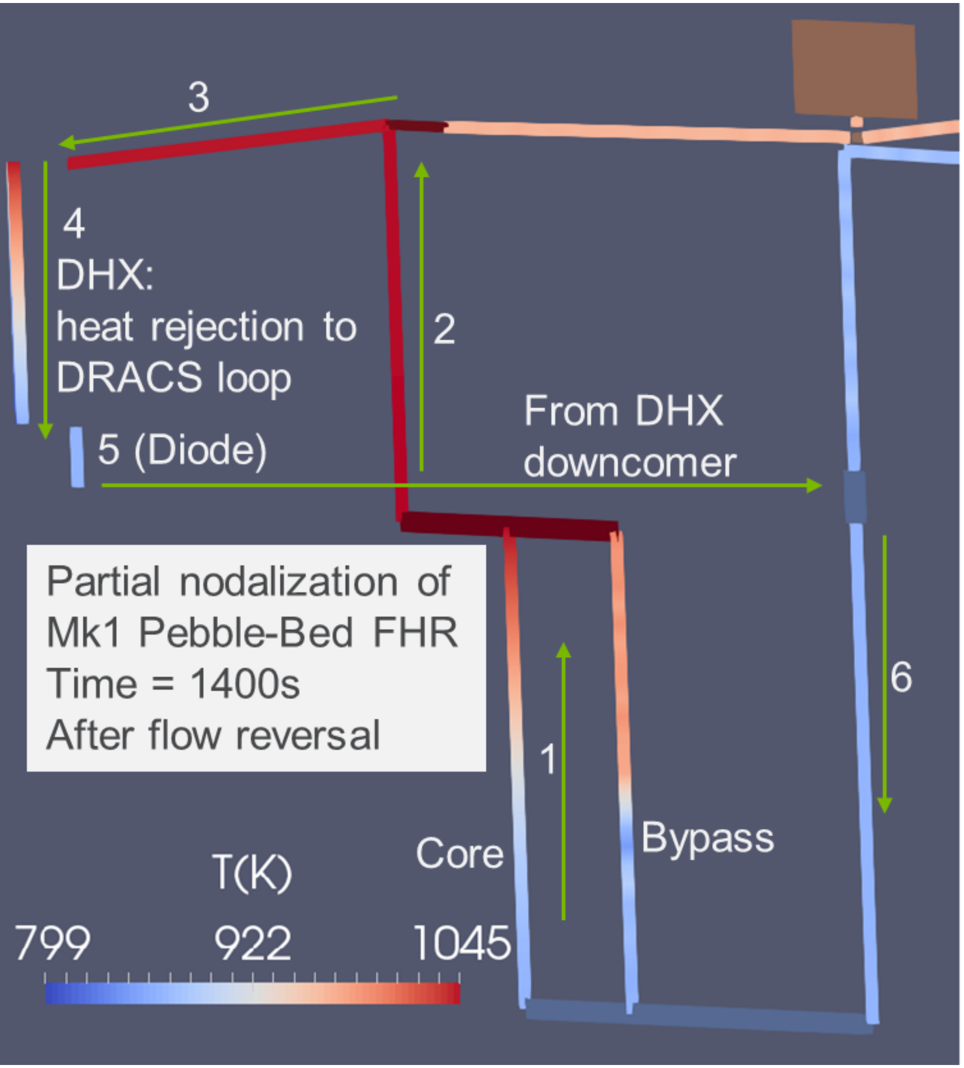


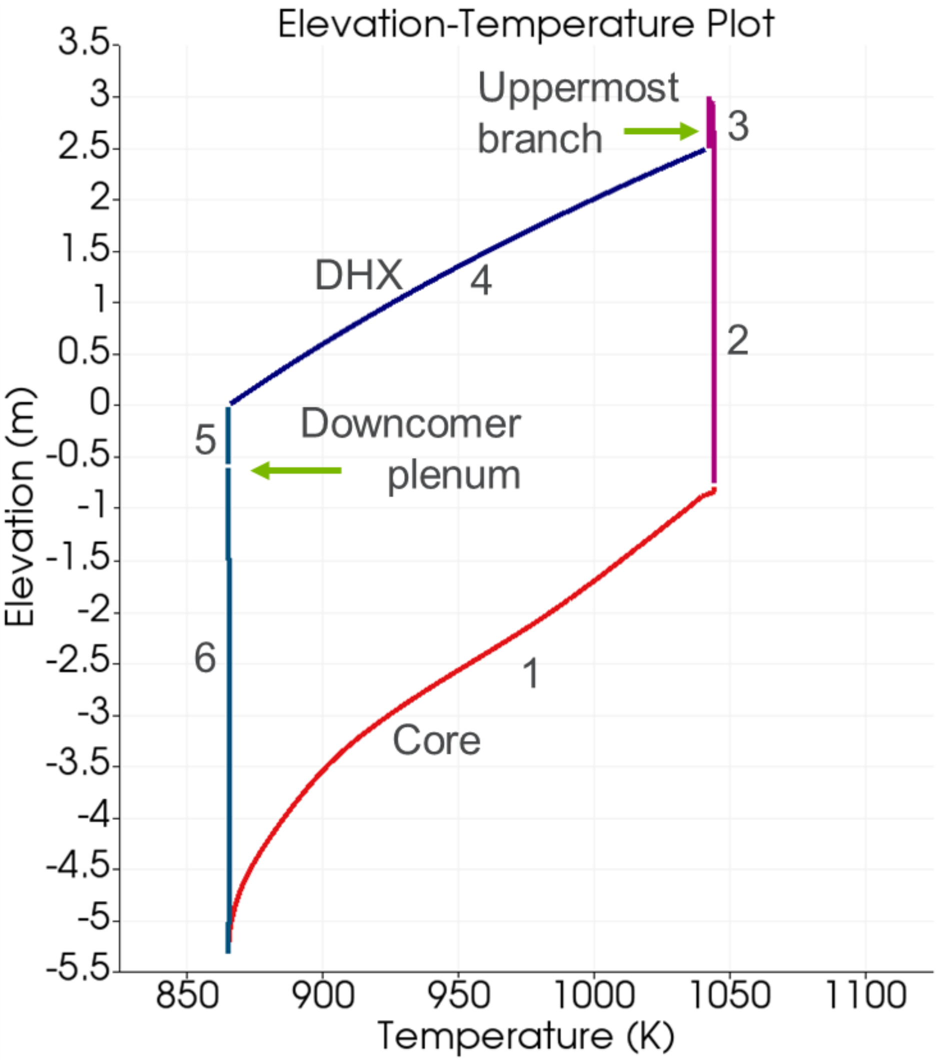
Transient Results: Flow Reversal



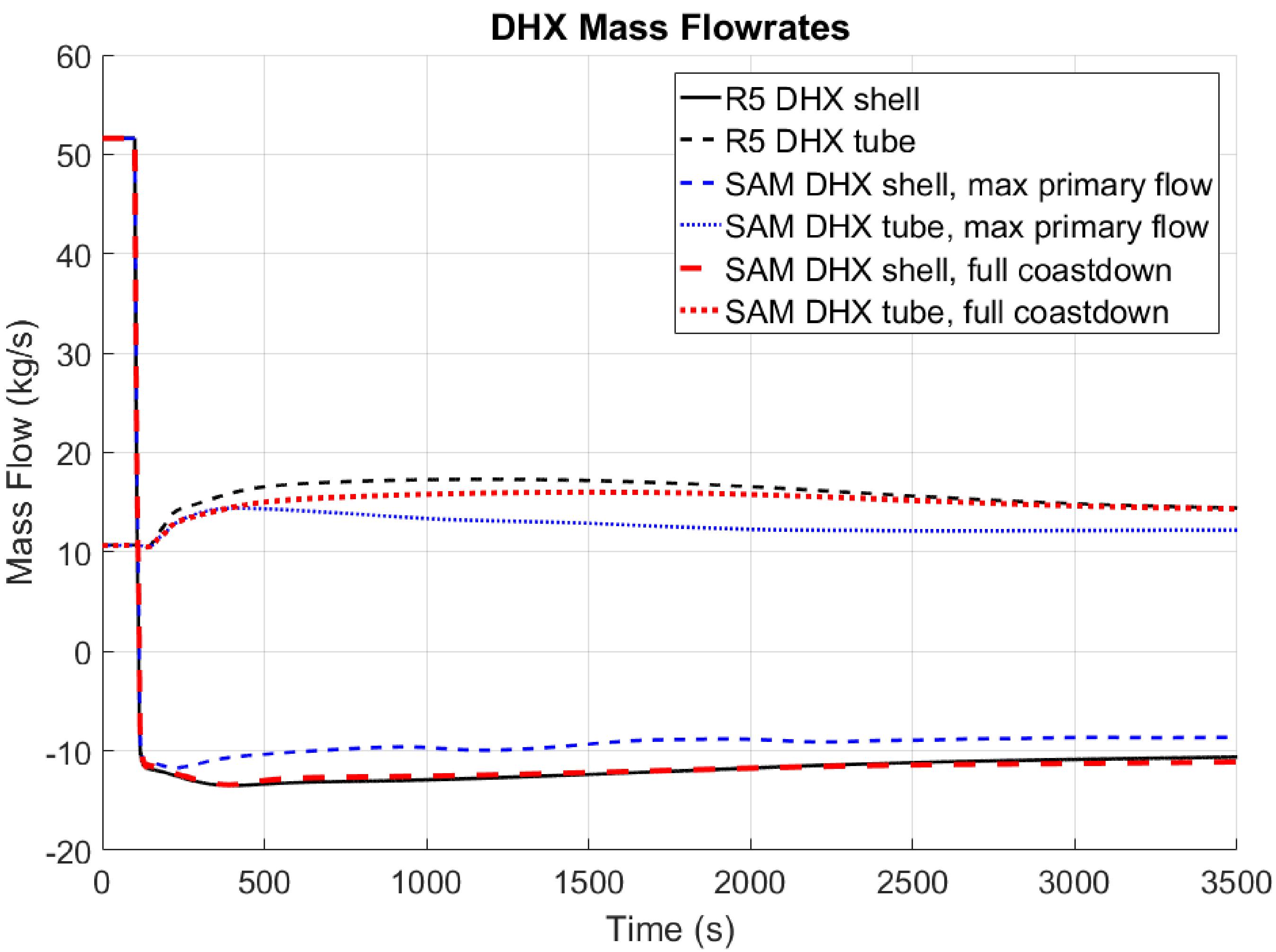


Transient Results: Flow Reversal

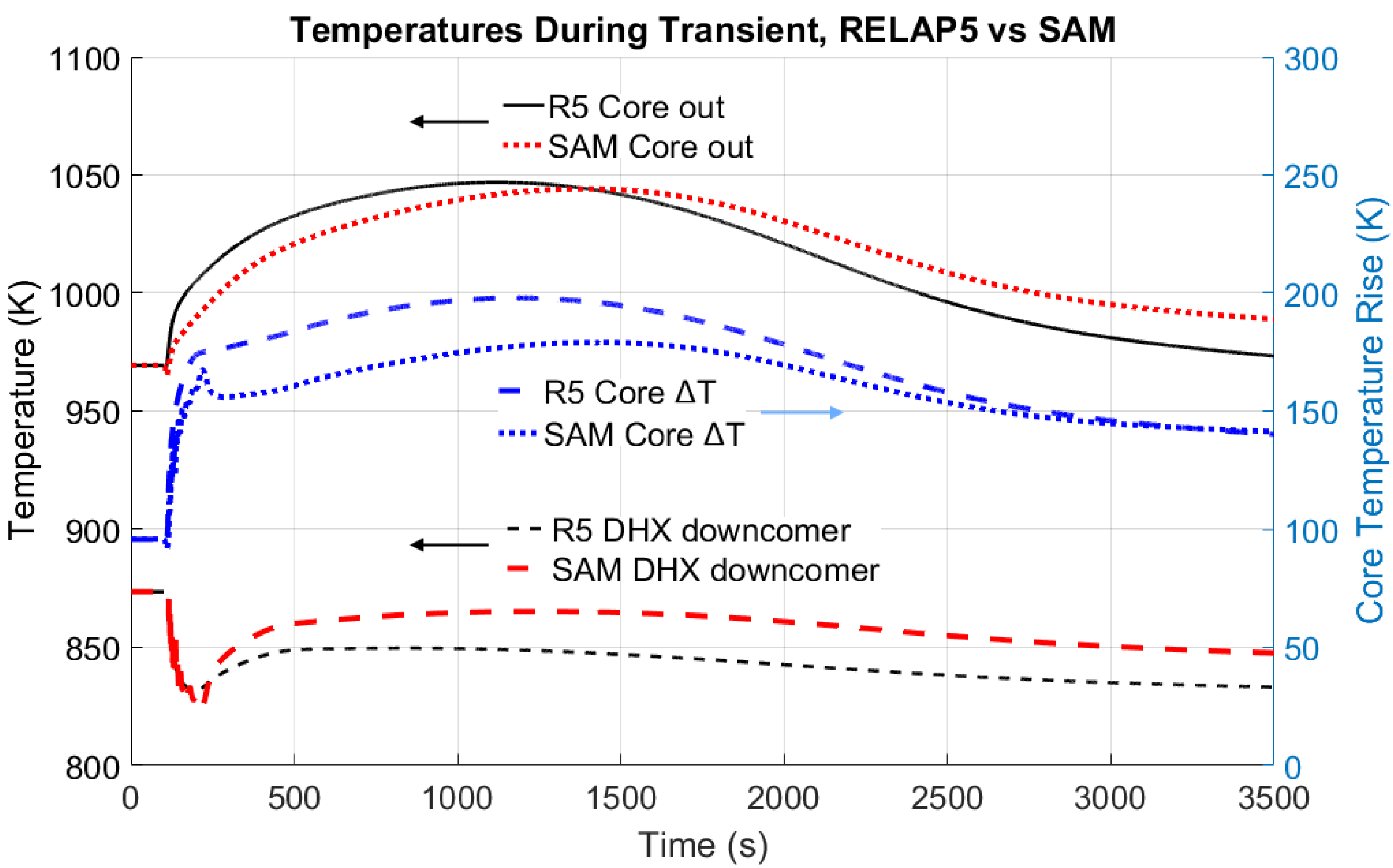




Transient Results: Flow Reversal



Transient Results: Key Temperatures



Conclusions and Path Forward

- Overall behavior including flow rates during reversal are well-captured
- Discrepancies arise from pump modeling and core heat structure treatment
- Future benchmark worth doing if spherical core heat structures used
  - Furthermore, code comparison could be done with more advanced RELAP model
  - Consider development of pump geometry, 3D flow model, porous medium approach
- Study opens discussion about passive safety system performance
- Benchmarking validation study with Compact Integral Effects Test (CIET) facility at UC-Berkeley also under consideration
- Continued development of overcooling simulation capability in SAM

Acknowledgements

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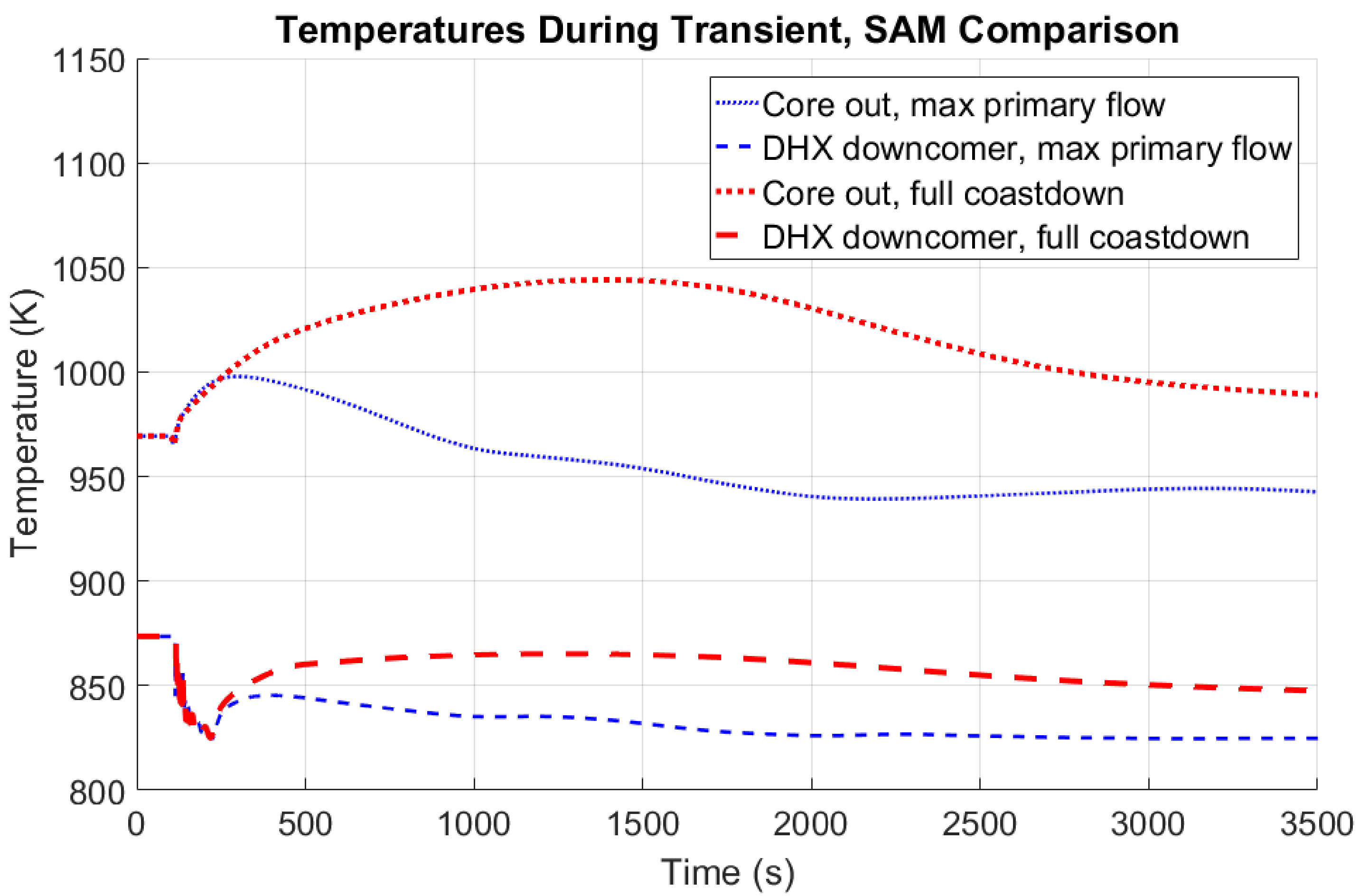
1. R. Hu, "SAM Theory Manual," ANL/NE-17/4, Argonne National Laboratory (2017).
2. N. Zweibaum, "Experimental Validation of Passive S Safety System Models: Application to Design and Optimization of Fluoride-Salt-Cooled, High-Temperature Reactors," PhD dissertation, University of California, Berkeley, available: http://www.nzweibaum.com/ (2015).
3. R. O. Scarlat, "Design of Complex Systems to Achieve Passive Safety: Natural Circulation Cooling of Liquid Salt Pebble Bed Reactors," PhD dissertation, University of California, Berkeley (2012).
4. C. B. Davis, "Implementation of Molten Salt Properties into RELAP5-3D/ATHENA," INEEL/EXT-05-02658, Idaho National Engineering and Environmental Laboratory (2005).
5. R. Hu, "Development of a Reduced-Order Three-Dimensional Fluid Model for Thermal Mixing and Stratification Simulation during Reactor Transients," Proceedings of 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Xi'an China, September 3 - 8, 2017.

Thanks for your attention

Backup Slides

Key Transient Temperatures, Two Extreme Cases



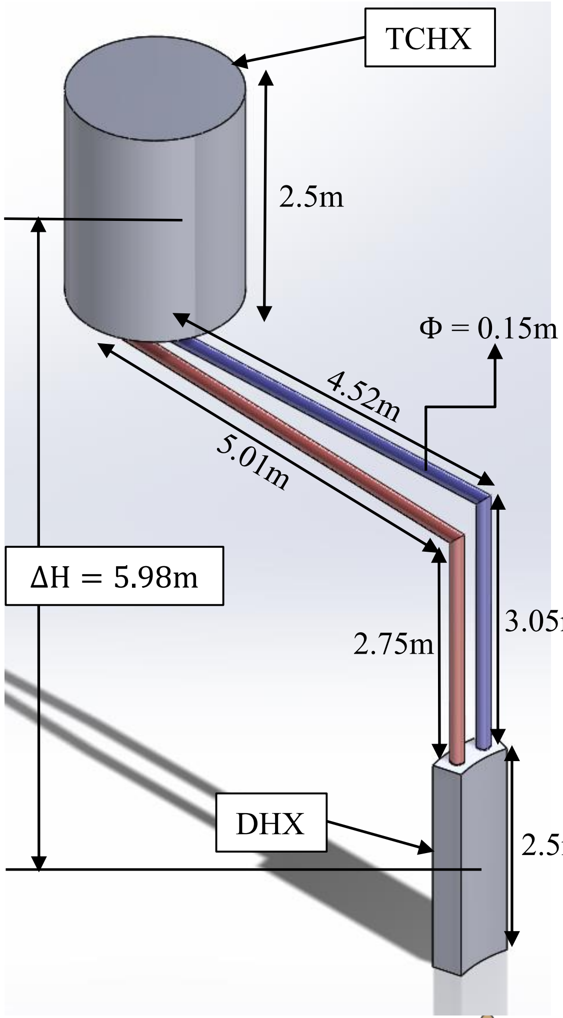
DHX-TCHX Natural Circulation Loop

Mk1 design parameters for DHX (tube side) and TCHX (coiled tube side)

Parameter	DHX	TCHX	Unit
Water Temperature (T_∞)	-	100	°C
Outside diameter	0.0127	0.0127	m
Inside diameter	0.0109	0.0109	m
Number of tubes	984	936	-
Tube length	2.5	6	m
Overall U	291	22.6	W/m^2-C
Heat Transfer Area	98	224	m^2

Liquid thermophysical properties for FLiBe (600-800°C)

Property	Correlation (T in °C)	Unit
Viscosity	$4.638 \cdot 10^5 / T^{2.79}$	kg/m-s
Specific Heat	2415.78	J/kg-C
Thermal Conductivity	$0.7662 + 0.0005 \cdot T$	W/m-C
Density	$2279.92 - 0.488 \cdot T$	kg/m^3



Building Mk1 PBFHR: Properties

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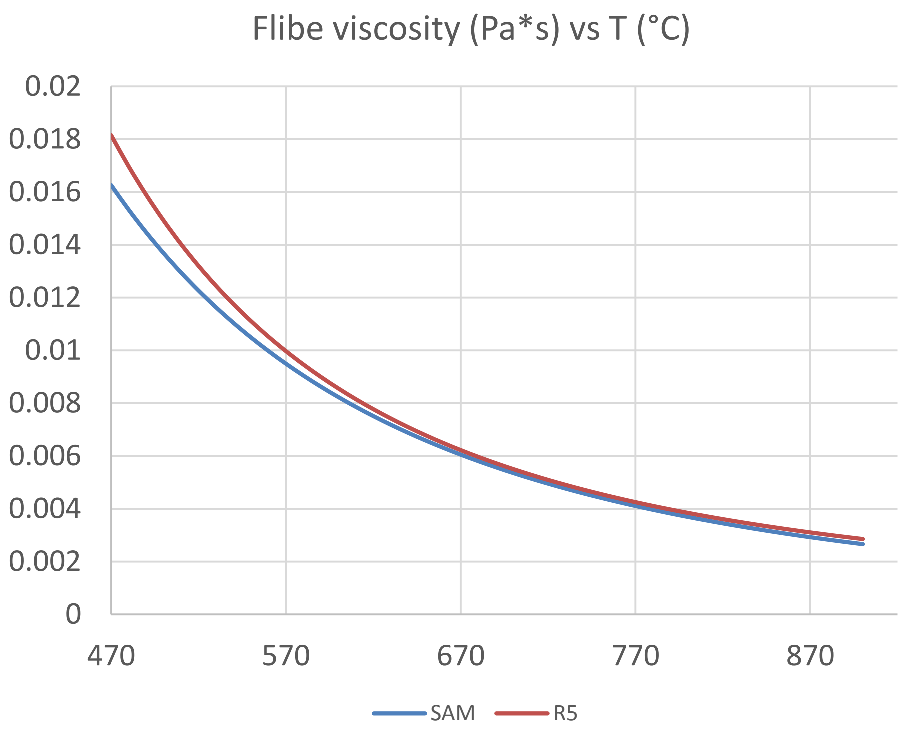
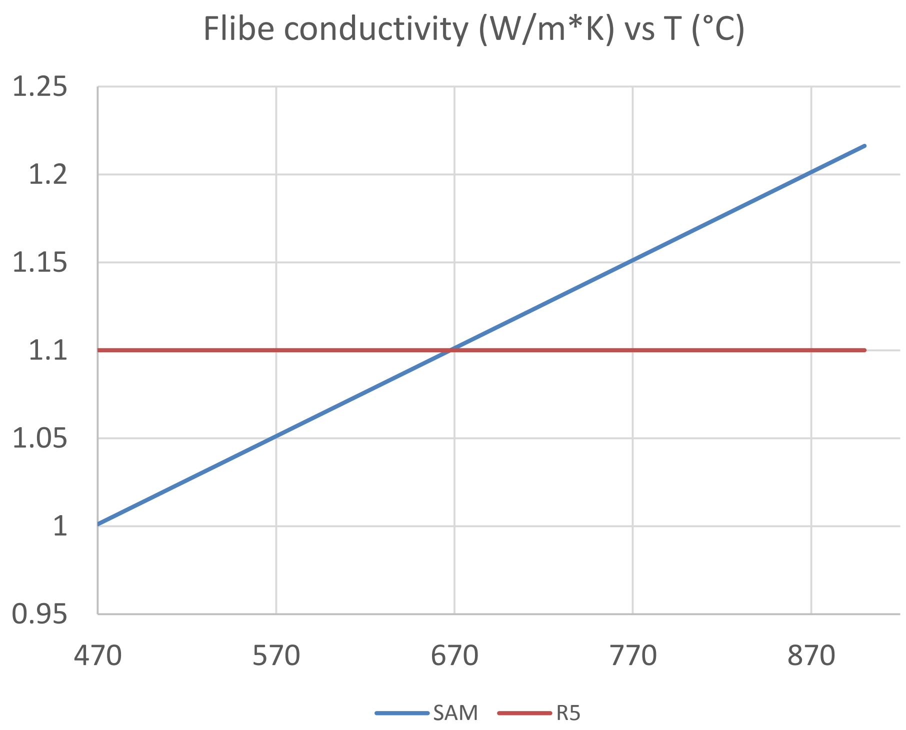
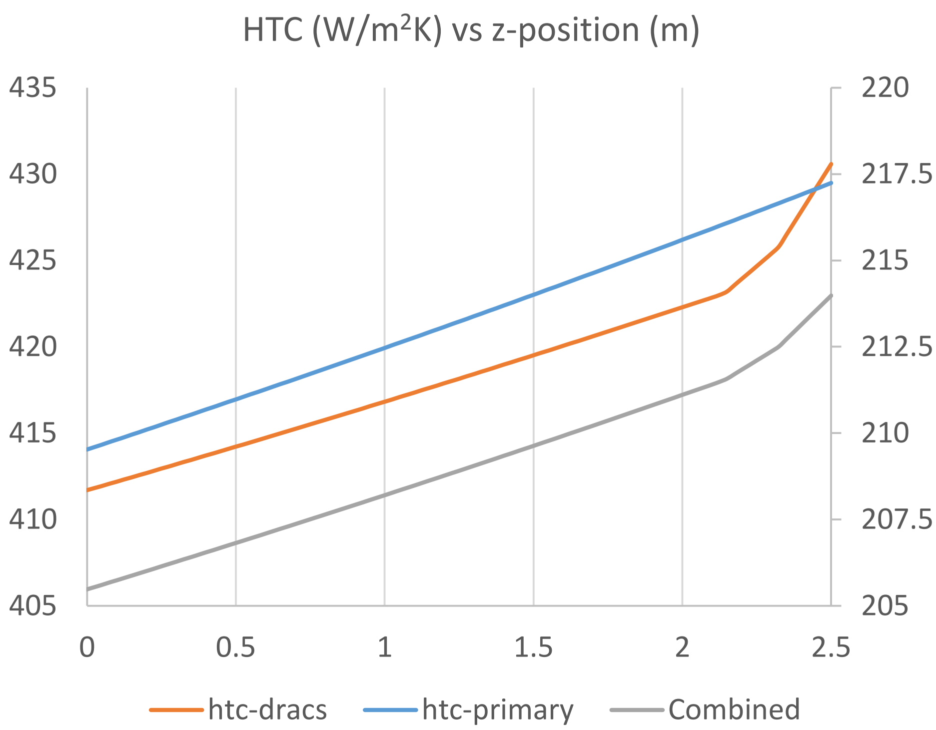
- For purpose of comparison, RELAP5 (R5) version implemented in SAM

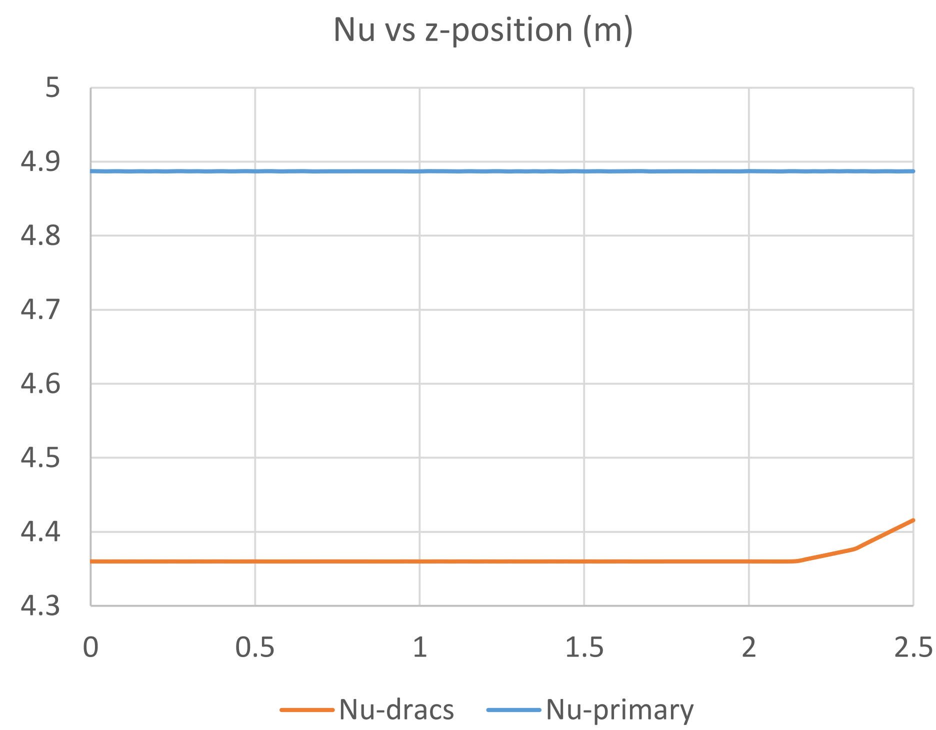




Aside: Example of h Calculation

- Heat transfer correlation selected based on Re, Pr





- $Nu = \frac{hL}{k}$ $\quad Re = \frac{\rho v D}{\mu}$ $\quad Pr = \frac{c_p \mu}{k}$ $\quad q'' = h(T_1 - T_2)$

Parameters Used in PB-FHR Models

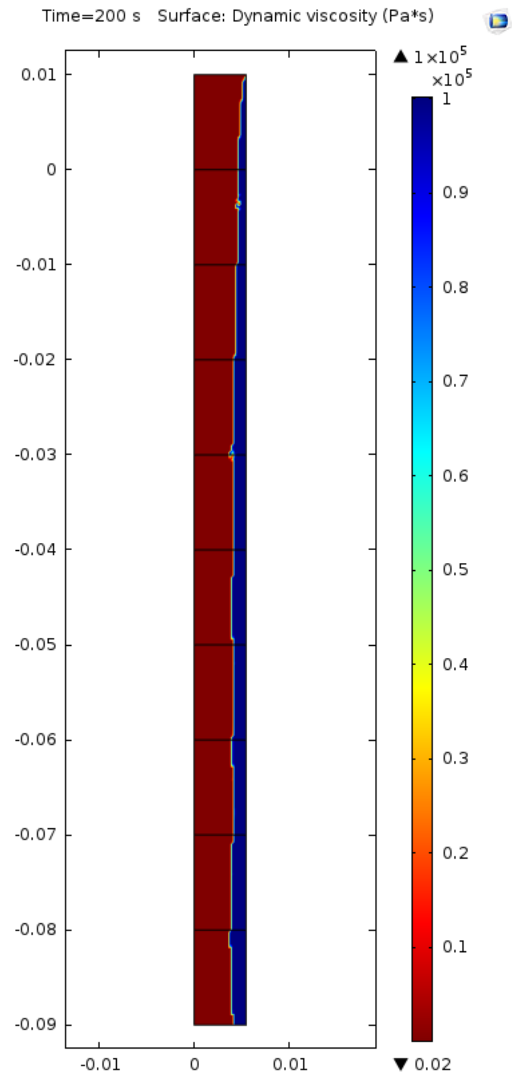
Component	Number on diagram	Length (m)	Vertical angle (°)	Hydraulic diameter (m)	Flow area (m2)
Core branch (bottom to top)					
Active core region	1	4.58	90	3.00E-02	1.33E+00
Core bypass	2	4.58	90	1.00E-02	1.33E-01
Hot salt collection ring	3	3.96	0	5.67E-01	2.52E-01
Hot salt extraction pipe	4	3.77	90	5.66E-01	2.51E-01
Branch	26	0.5	0	5.80E-01	2.64E-01
CTAH branch (top to bottom)					
Reactor vessel to hot salt well	5	3.73	1.2443	5.80E-01	2.64E-01
Hot salt well	6	2	9.7878	1.45E+00	3.31E+00
Hot salt well to CTAH	7	3.23	-0.8160	4.40E-01	3.04E-01
CTAH hot manifold	8	3.418	-90	2.80E-01	4.93E-01
CTAH salt side	9	18.47	-0.5088	4.57E-03	4.49E-01
CTAH cold manifold	10	3.418	-90	1.75E-01	1.92E-01
CTAH to drain tank	11	3.48	-1.2349	4.38E-01	3.02E-01
Stand pipe	12	6.51	90	4.38E-01	3.02E-01
Stand pipe to reactor vessel	13	6.6033	1.2148	4.38E-01	3.02E-01
Injection plenum	14	3.04	-90	4.38E-01	3.02E-01
Branch	27	0.5	-90	5.60E-02	3.04E-01
Downcomer	15	4.76	-90	5.60E-02	3.04E-01
Inlet plenum	28	0.2	0	3.00E-02	1.33E+00

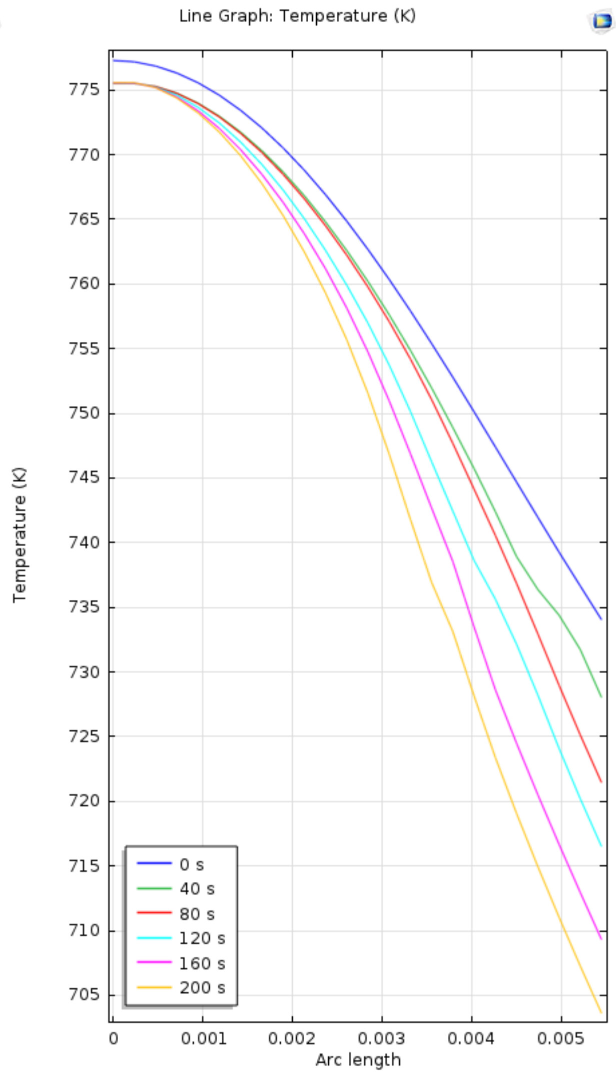
Parameters Used in PB-FHR Models

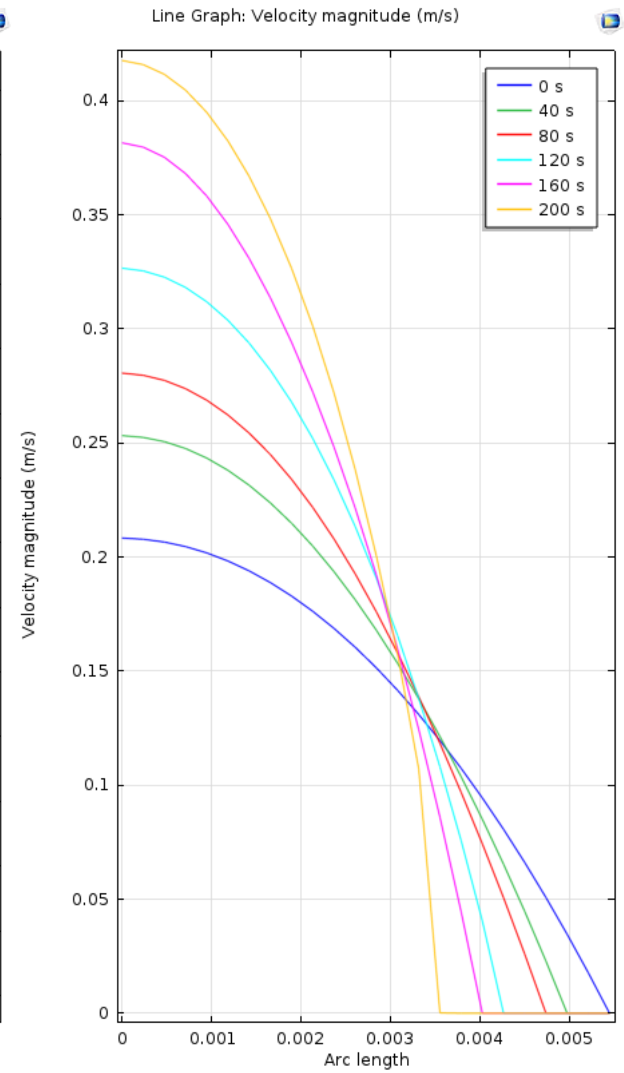
Component	Number on diagram	Length (m)	Vertical angle (°)	Hydraulic diameter (m)	Flow area (m2)
DHX branch (bottom to top)					
Downcomer to DHX	16	0.58	90	1.50E-01	3.53E-02
DHX shell side	17	2.5	90	1.09E-02	2.22E-01
DHX to hot leg	18	3.008	9.7615	1.50E-01	3.53E-02
DRACS loop (counterclockwise)					
DHX tube side	19	2.5	90	1.09E-02	1.84E-01
DRACS hot leg 1	20	3.45	90	1.50E-01	3.53E-02
DRACS hot leg 2	21	3.67	0	1.50E-01	3.53E-02
TCHX manifold	22	2.6	90	1.50E-01	3.53E-02
TCHX salt tube	23	6	-25.6793	1.09E-02	1.75E-01
DRACS cold leg 1	24	4.43	0	1.50E-01	3.53E-02
DRACS cold leg 2	25	5.95	-90	1.50E-01	3.53E-02

Heat Structure Component	Number on diagram	Length (m)	Left boundary (m)	Wall thickness (m)
CTAH salt side	9	18.47	2.29E-03	8.89E-04
DHX tube side	19	2.5	5.45E-03	9.00E-04
TCHX salt tube	23	6	5.45E-03	9.00E-04

Overcooling Modeling in CFD







Overcooling Model for System Code

Fluid Pressure

$$\frac{\partial (A\rho)_l}{\partial t} + \frac{\partial (A\rho u)_l}{dz} = -\sigma_A$$

Fluid Velocity

$$\frac{\partial (A\rho u)}{\partial t} + \frac{\partial (A\rho uu + Ap)}{dz} = -A\rho g - \frac{Af}{D}\frac{\rho u|u|}{2}$$

Fluid Temperature

$$\frac{\partial (A\rho H)_l}{\partial t} + \frac{\partial (A\rho u H)_l}{dz} = -\sigma_A H + q'_{wl}(T_l > T_f) + q'_{int}(T_l \leq T_f)$$

Solid Temperature

$$\frac{\partial (A\rho H)_s}{\partial t} = \sigma_A H_s + q'_{ws} - q'_{int}$$

Solid Mass

$$\frac{\partial (A\rho)_s}{\partial t} = \sigma_A$$

Interface Radius

$$\left(\frac{-q''_{ws}R}{r} - h_{int}(T_m - T_l)\right) = \left(1 + \left(\frac{dr_i}{dz}\right)^2\right)\frac{\partial r_i}{\partial t}(\rho \Delta H)$$