C1Or2B-04: Numerical modelling of the cool-down of the helium transfer-lines for FRIB Linac and experimental systems

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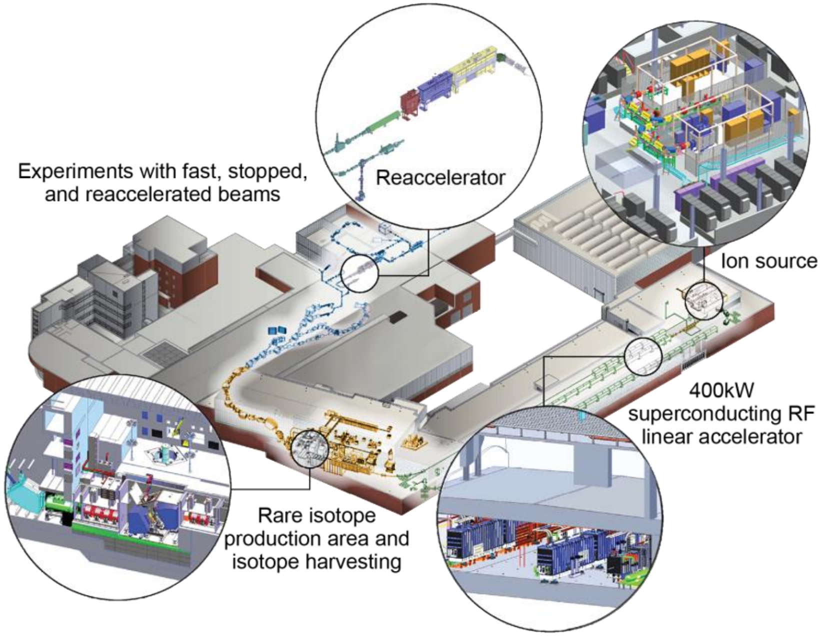
Background [1]

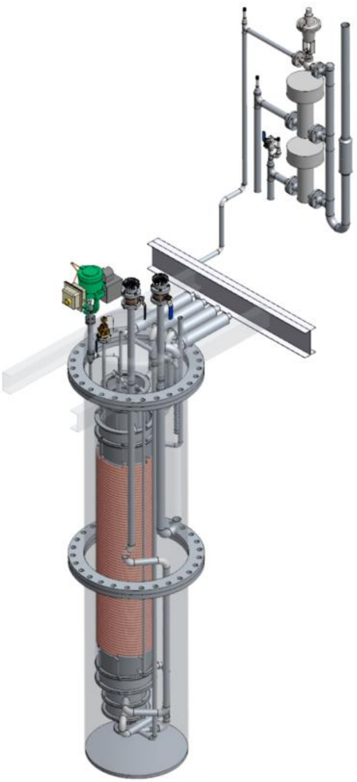
- The cryogenic distribution system at FRIB is separated into four segments
- These four distribution segments (or cryogenic transfer lines) are independently connected to the FRIB cryogenic refrigeration system
- Any of them can be disconnected or operated at different process conditions



- In the past, cool-down of these cryogenic transfer lines and associated loads (superconducting magnets) with 4.5 K liquid helium has been used
- Typically, a cool-down flow with approximately 50 K temperature differential (between the supply and return cooling flow) is preferable

Background [2]

- FRIB developed a cool-down heat exchanger system (Hasan *et al.*, 2021)
- Objective: develop and validate a numerical model for predicting the transient cool-down process of the cryogenic transfer line segments at FRIB
  - Using gaseous helium flow maintaining the prescribed temperature differential (50 K) between the supply and return flow
- It is a 1-D, transient, thermal-hydraulic model
- Solves:
  - Separate fluid and pipe temperatures
  - Fluid pressure distribution and mass flow
  - Several piping components are incorporated and their impact on the thermal-hydraulic characteristics are simulated
- Development and validation of the model, as well as the transient cool-down process in two different cryogenic transfer lines at FRIB are discussed



FRIB Cool-down Heat Exchanger Cold Box

Problem Domain [1]

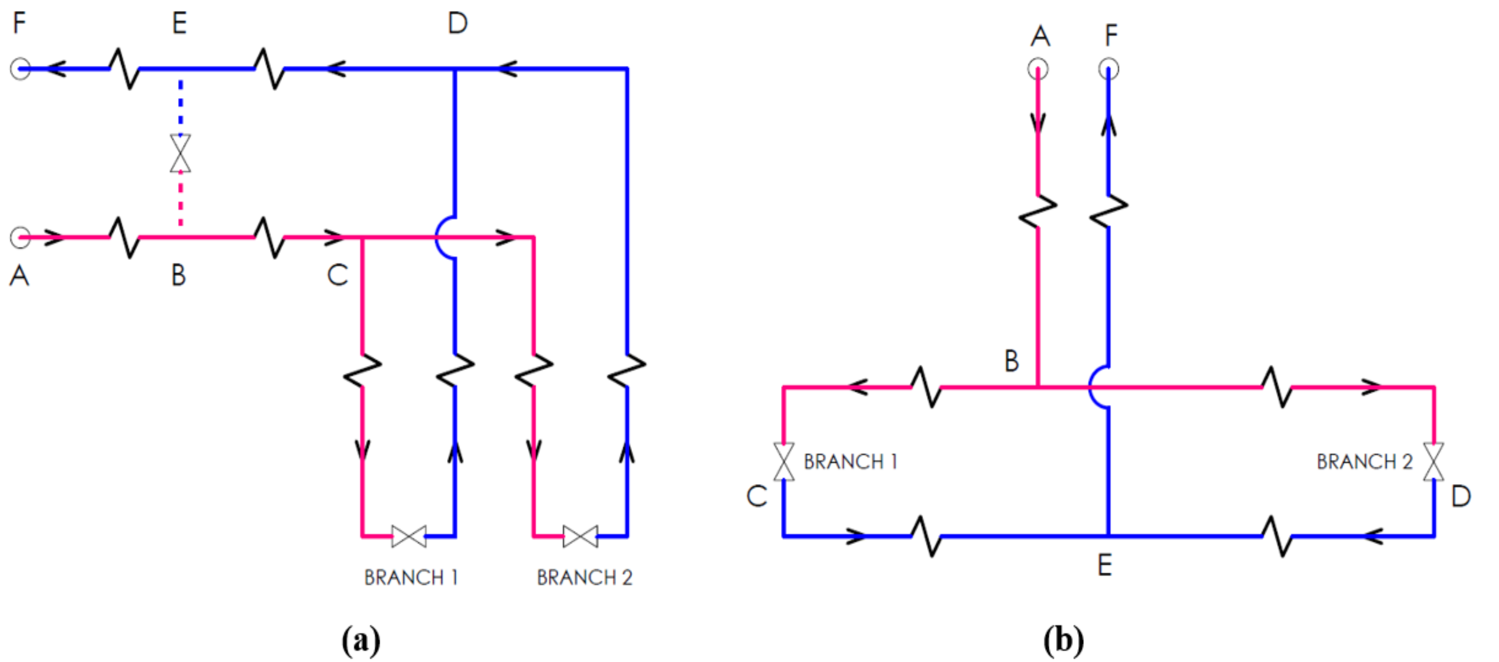
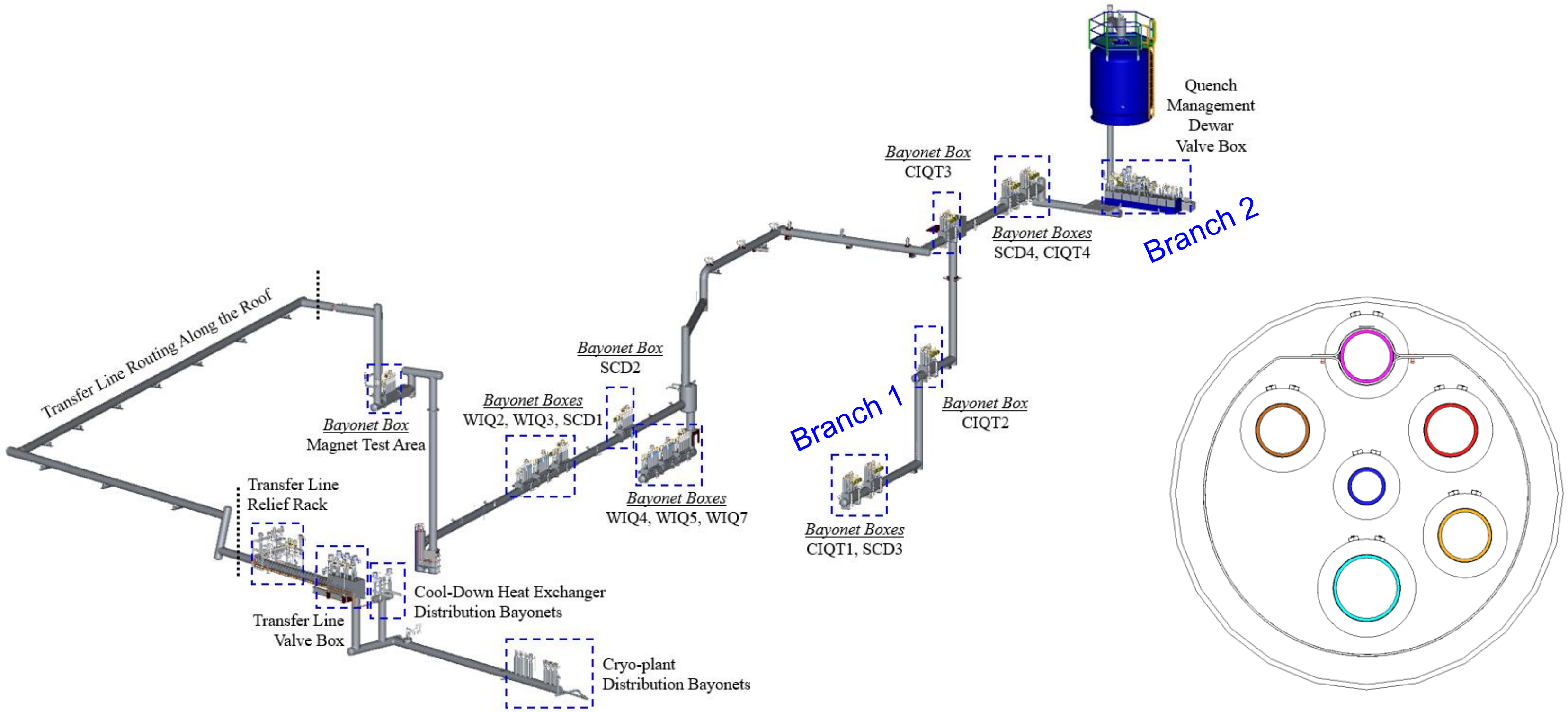


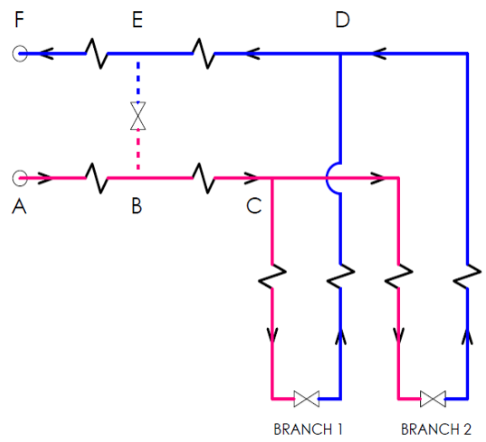
Fig. Schematic diagram of the problem domain for simulating (a) FRIB experimental system, and (b) FRIB LINAC segment 2 cryogenic transfer line.

Problem Domain – FRIB Exp. System [2]



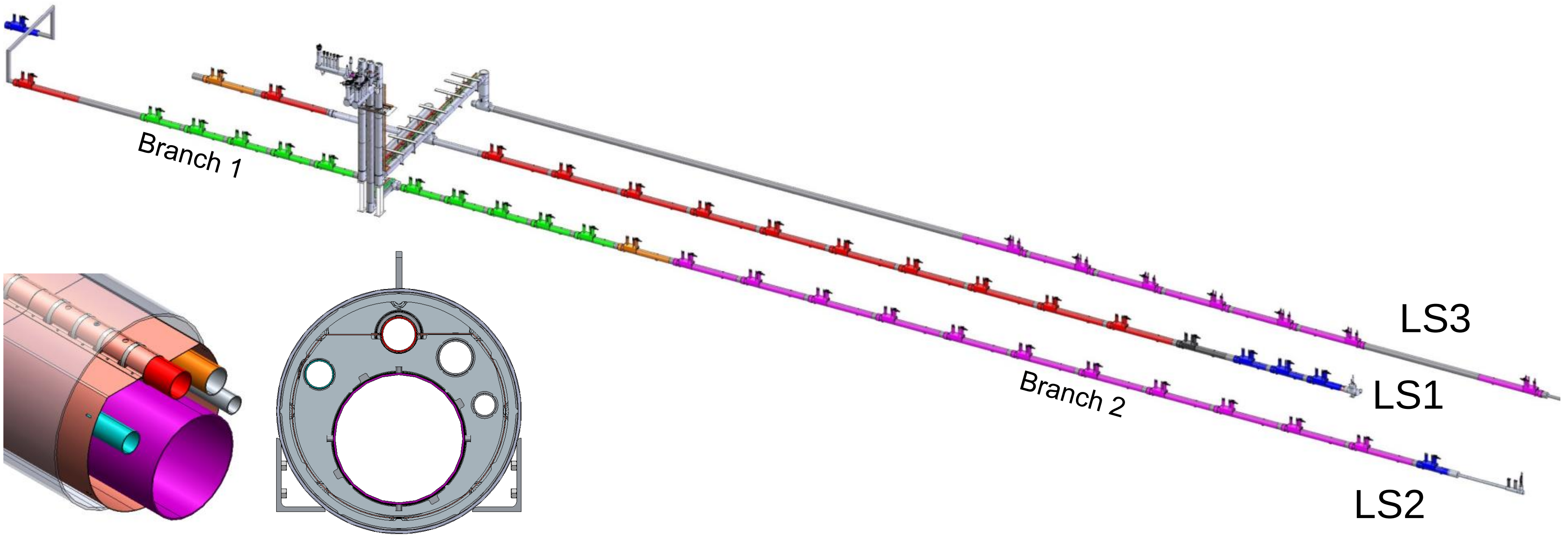
- The experimental system cryogenic transfer line is shown with two branches
  - Branch 1 represents the vertical pre-separator area and branch 2 represents the quench dewar area
  - A third (shorter) loop is also shown (A-B-E-F)
    - This represents the magnet test station at the FRIB experimental system

Problem Domain – FRIB Exp. System [3]



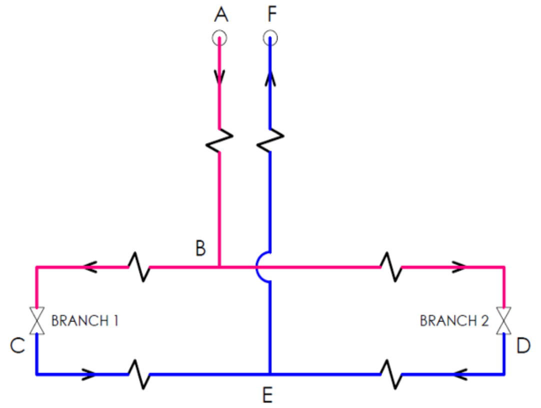
Section	Line Size (NPS)	Length [m]	Piping Components					
			Exp. Jnt	Elbow	Valve	Guide	Anchor	V.B.
A-B	1.5	54.5	9	8	0	14	8	1
B-C	1.5	67.0	12	10	0	18	10	1
C-D (Br 1)	1.5	39.0	8	10	1	12	10	0
C-D (Br 2)	1.5	26.0	8	6	1	14	6	0
D-E	1.5	67.0	12	10	0	18	10	1
E-F	1.5	54.5	9	8	0	14	8	1

Problem Domain – FRIB LINAC Segment 2 [4]



- The LINAC segment 2 cryogenic transfer line is shown with the two branches
  - Branch 1 is shorter, supporting 6 cryo-modules and branch 2 is significantly longer supporting 18 cryo-modules

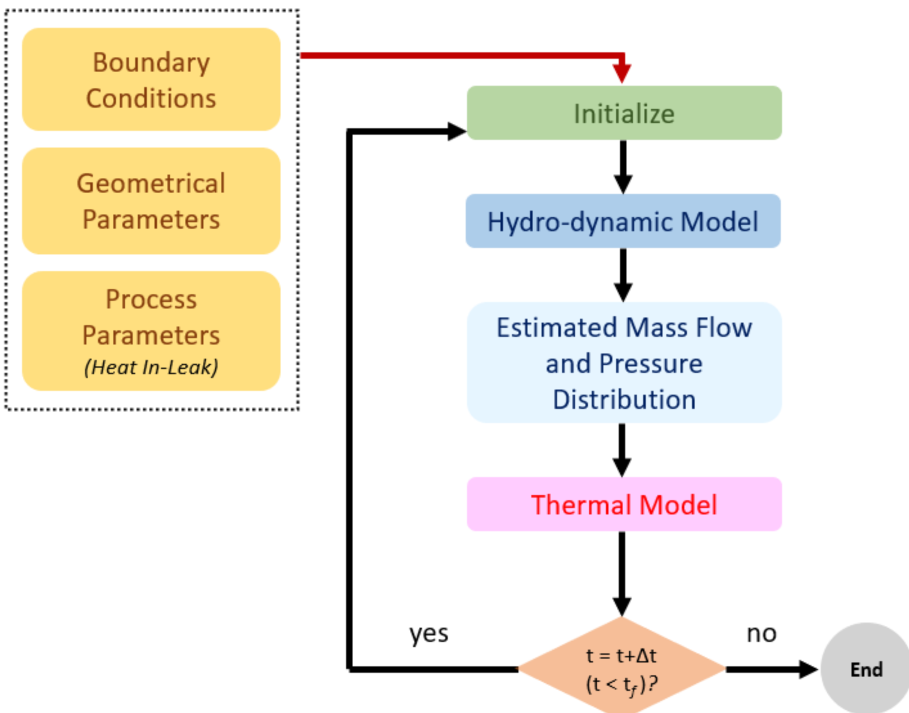
Problem Domain – FRIB LINAC Segment 2 [5]

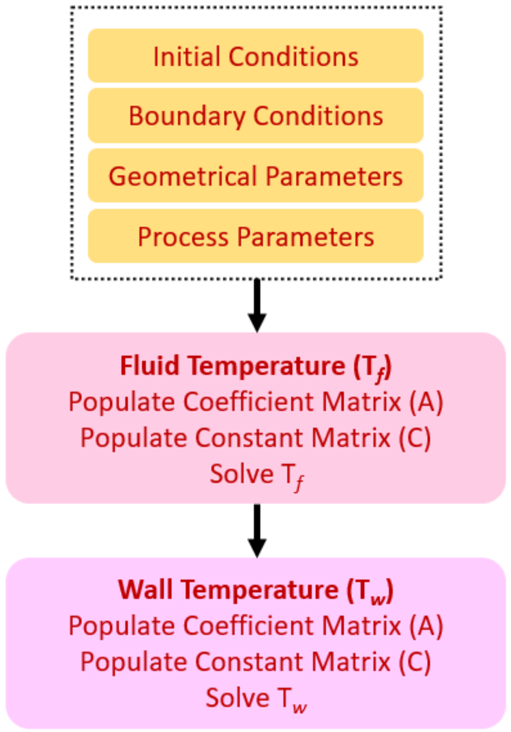


Section	Line Size (NPS)	Length [m]	Piping Components (Qty)					
			Exp. Jnt	Elbow	Valve	Guide	Anchor	V.B.
A-B	1.5	56.0	4	3	0	6	4	0
B-C (Br 1)	1.5	25.5	3	1	1	6	3	0
C-E (Br 1)	10	21.0	3	1	0	6	3	0
B-D (Br 2)	1.5	105.0	9	1	1	18	9	0
D-E (Br 2)	10	99.5	9	1	0	18	9	0
E-F	10	56.0	4	3	0	6	4	0

Model Development [1]

- The numerical model is developed modularly with three separate modules
  - Geometrical parameters (incorporating pipe diameter, lengths and piping components for different segments)
  - Hydrodynamic parameters (fluid pressure distribution and mass flow)
  - Temperature distribution (Gas and Solid)





Model Development [2]

- The hydrodynamic model is a one-dimensional pseudo-steady hydraulic simulator solving:
  - Pressure distribution across the cryogenic transfer line
  - Mass flow rates based on the specified boundary pressure differential (inlet 2.5 bar, outlet 1.2 bar)
  - Fluid and Piping temperature
- The hydraulic flow resistance for each relevant piping component (*e.g.,* pipe, elbow, and bellows) was developed following the equations found in Idelchik (1967)
- The pressure profile and mass flow rate are then iterated using secant method until convergence
- The hydrodynamic model is called at periodic time-steps with given temperature distribution to solve for the mass flow and pressure distribution

Model Development [3]

- The transient temperatures in the fluid and pipe wall are calculated by solving the conservation of energy equations:

$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} + \rho_f c_{p,f} u \frac{\partial T_f}{\partial x} = \dot{q}_{conv}$$

$$\rho_w c_w \frac{\partial T_w}{\partial t} = k_w \frac{\partial^2 T_w}{\partial x^2} - \dot{q}_{conv} + \dot{q}_{HIL}$$

  - Fluid advection and conduction are included, while the solid includes conduction term only
  - The advection velocity in the fluid is calculated based on the mean velocity in the pipe (from mass flow, and flow area)
  - Dittus-Boelter correlation is used to estimate the heat transfer coefficient in calculating the convective heat transfer

- Real fluid properties are considered, using CoolProps [11]

- For the solids, temperature dependent properties are used based on NIST TRC database

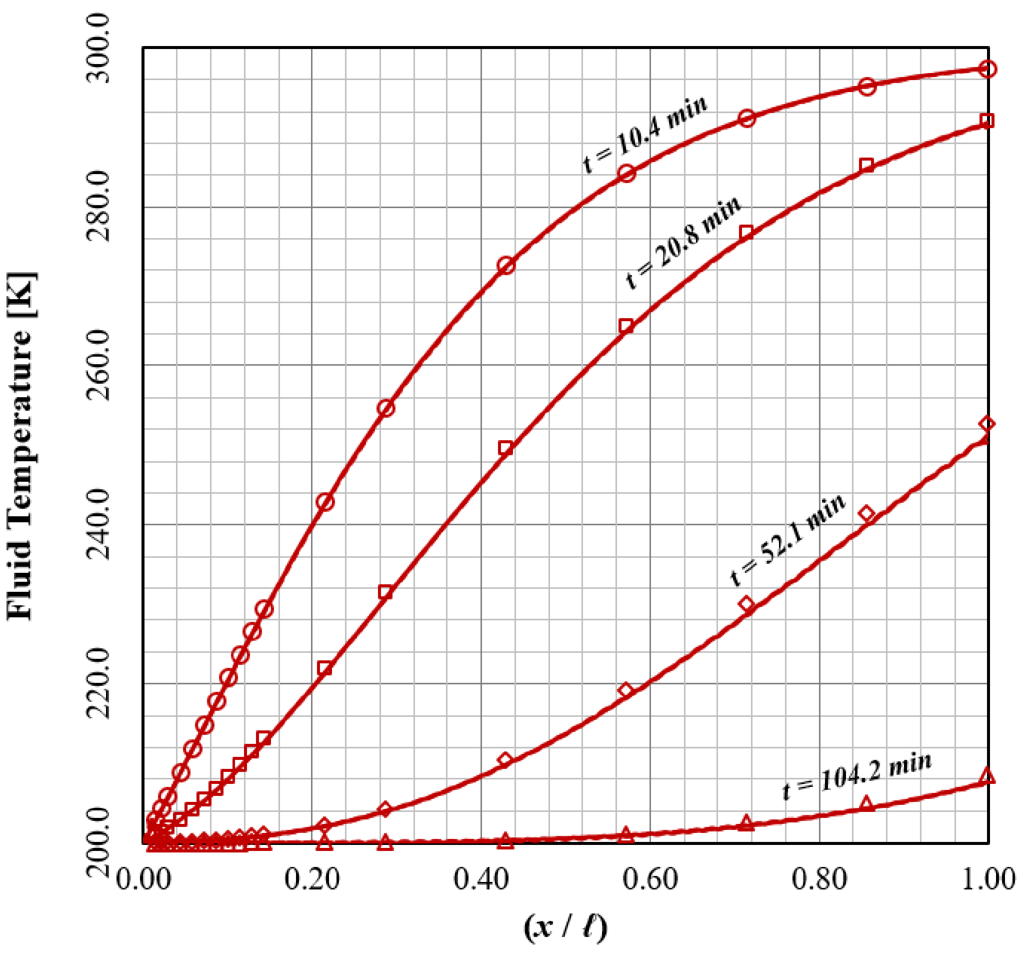
Model Development [3]

- Initially both fluid and the solid (pipe wall) are considered at rest and at ambient temperature ($T_0 = 300\ K$)

- The fluid temperature (T_f) at the inlet (x = 0) is specified – either constant or as a function of time, dependent on the outlet temperature maintaining the prescribed (50 K) temperature differential

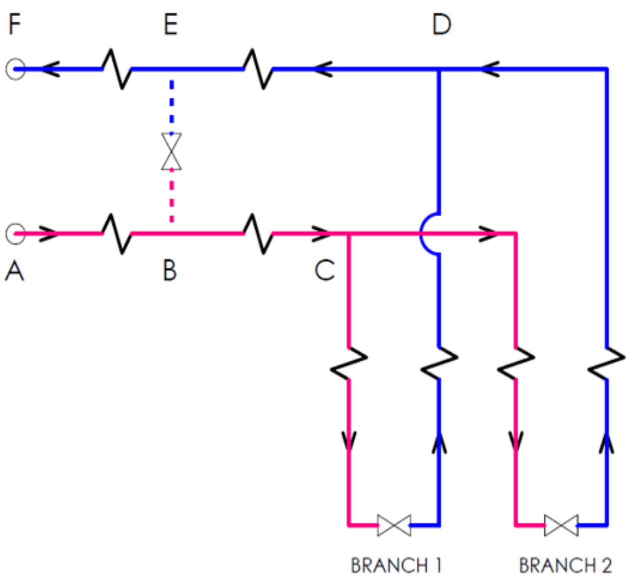
- Thermal interface boundary conditions at the branches are used maintaining continuity of temperature and heat flux

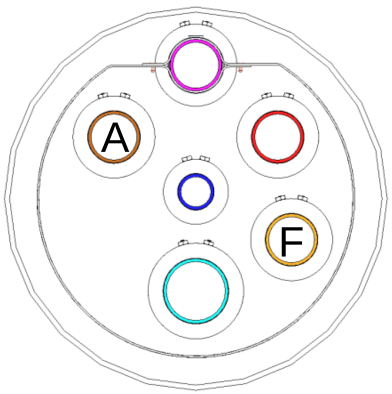
Model Validation [1]



- The thermal model was validated using a closed-form analytical solution
- A simple pipeline is considered for this validation
  - 55.0 m long pipeline
    - d_o = 48.26 mm, t = 2.77 mm)
  - Cool-down from 300 K to 200 K
  - 200 K helium gas (5.0 g/s)

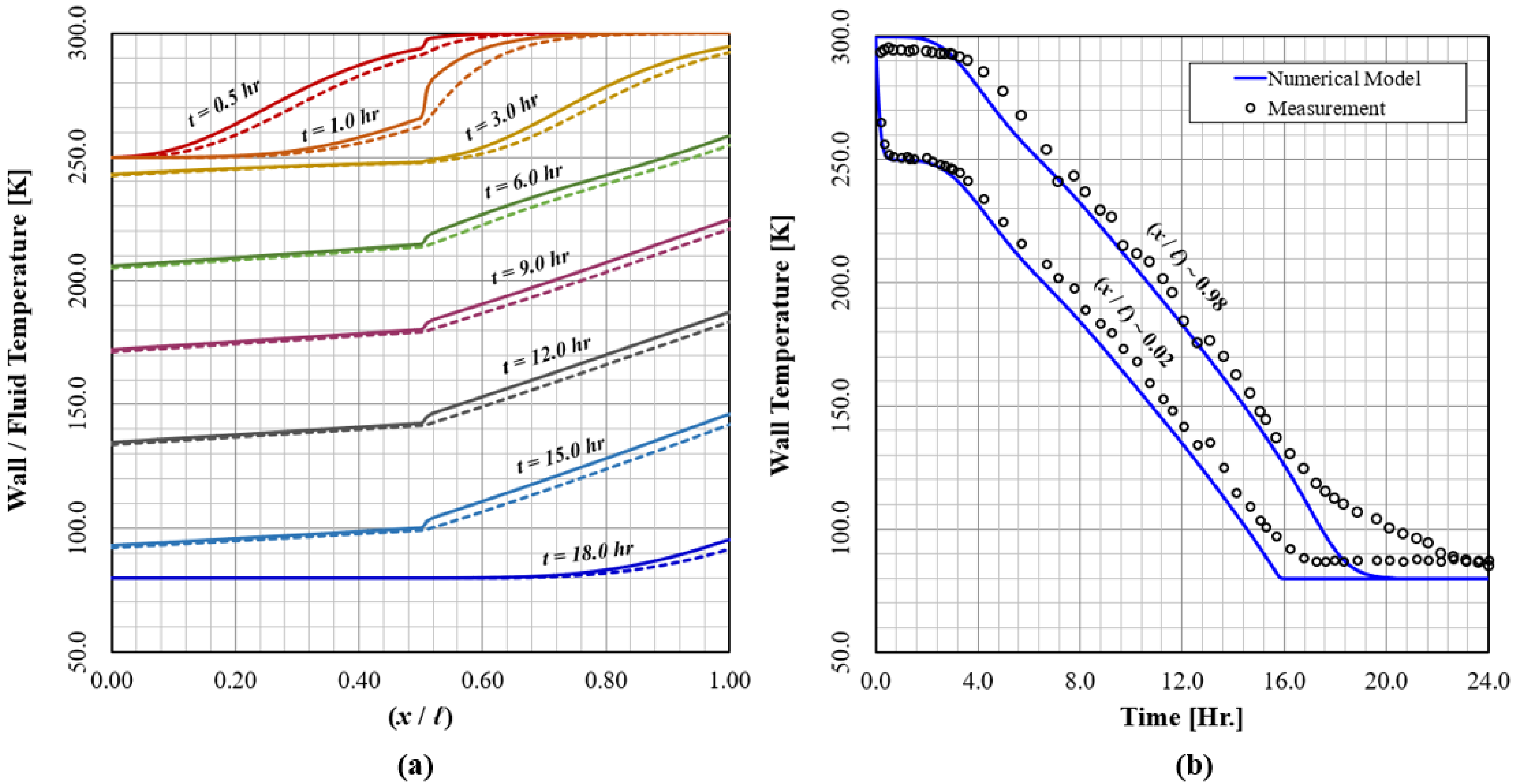
Cool-Down of FRIB Experimental System Cryogenic Distribution [1]





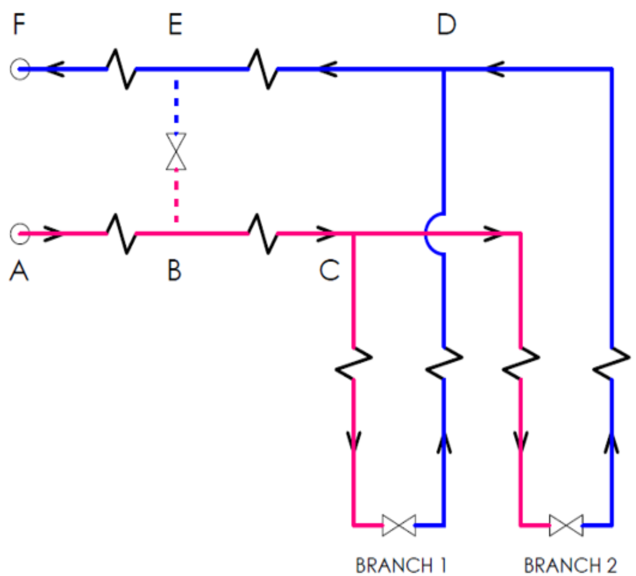
- Cool-down of FRIB experimental system cryogenic transfer line (A-B-E-F) shield circuit is considered
  - consists of an additional copper shield (d_o ~ 0.3 m, t ~ 1.6 mm) clamped to the segment E-F (at x/ℓ = 0.5-1.0) and surrounding the rest of the pipes
- Cool-down is performed with gaseous helium (maintained constant ~ 4.7 g/s)
- This phase of cool-down is carried out with a temperature differential of 50 K, until the entire pipeline reaches 80 K
- At this point, most of the thermal stresses associated with the cool-down are subsided
  - In practice, the following phases of the cool-down are carried out with 35 K / 4.5 K helium

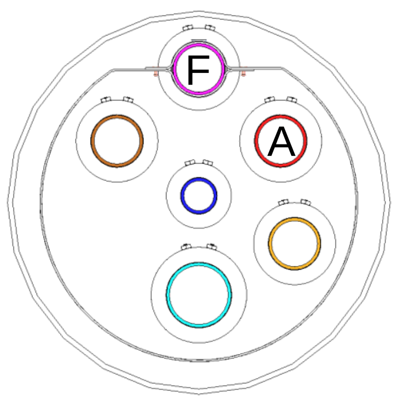
Cool-Down of FRIB Experimental System Cryogenic Distribution [2]



Calculated (a) spatial and (b) temporal distribution of fluid and pipe wall temperature for FRIB experimental system transfer line (section A-B-E-F only, thermal shield circuit)

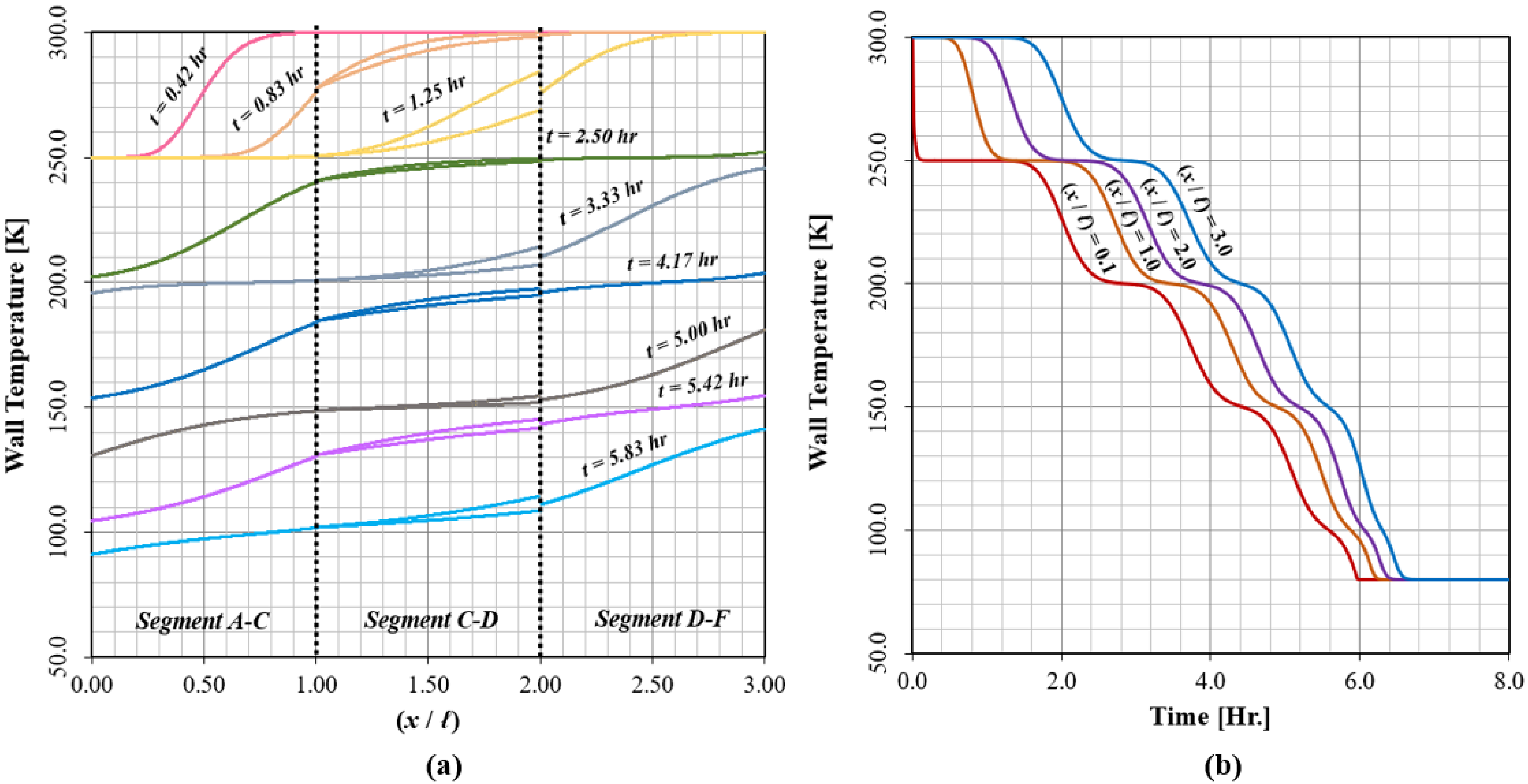
Cool-Down of FRIB Experimental System Cryogenic Distribution [3]





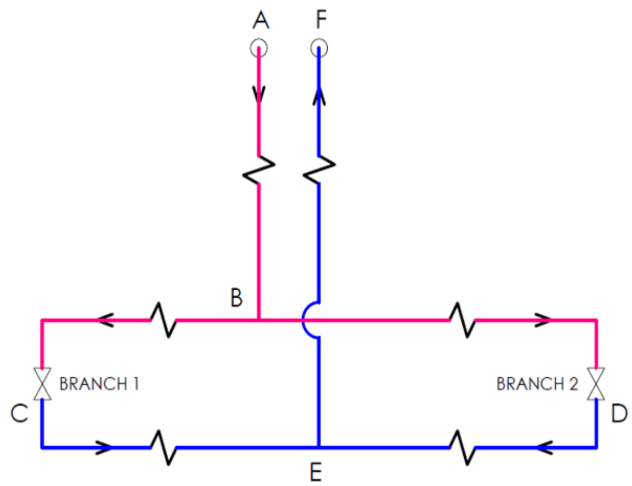
- Cool-down of FRIB experimental system cryogenic transfer line (A-B-C-D-E-F) cool-down circuit is considered
- The inlet (A) is maintained at 2.5 bar, and the outlet pressure is maintained at 1.2 bar
  - The overall mass flow and mass flow distribution across the two branches are calculated based on the component hydraulic resistance
- For this mode of operation, the flow path directly between B and F is closed

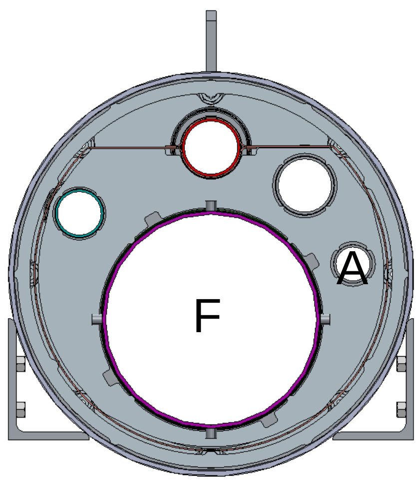
Cool-Down of FRIB Experimental System Cryogenic Distribution [4]



Calculated (a) spatial and (b) temporal distribution of pipe wall temperature for FRIB experimental system transfer line (section A-B-C-D-E-F, both branches, cool-down circuit)

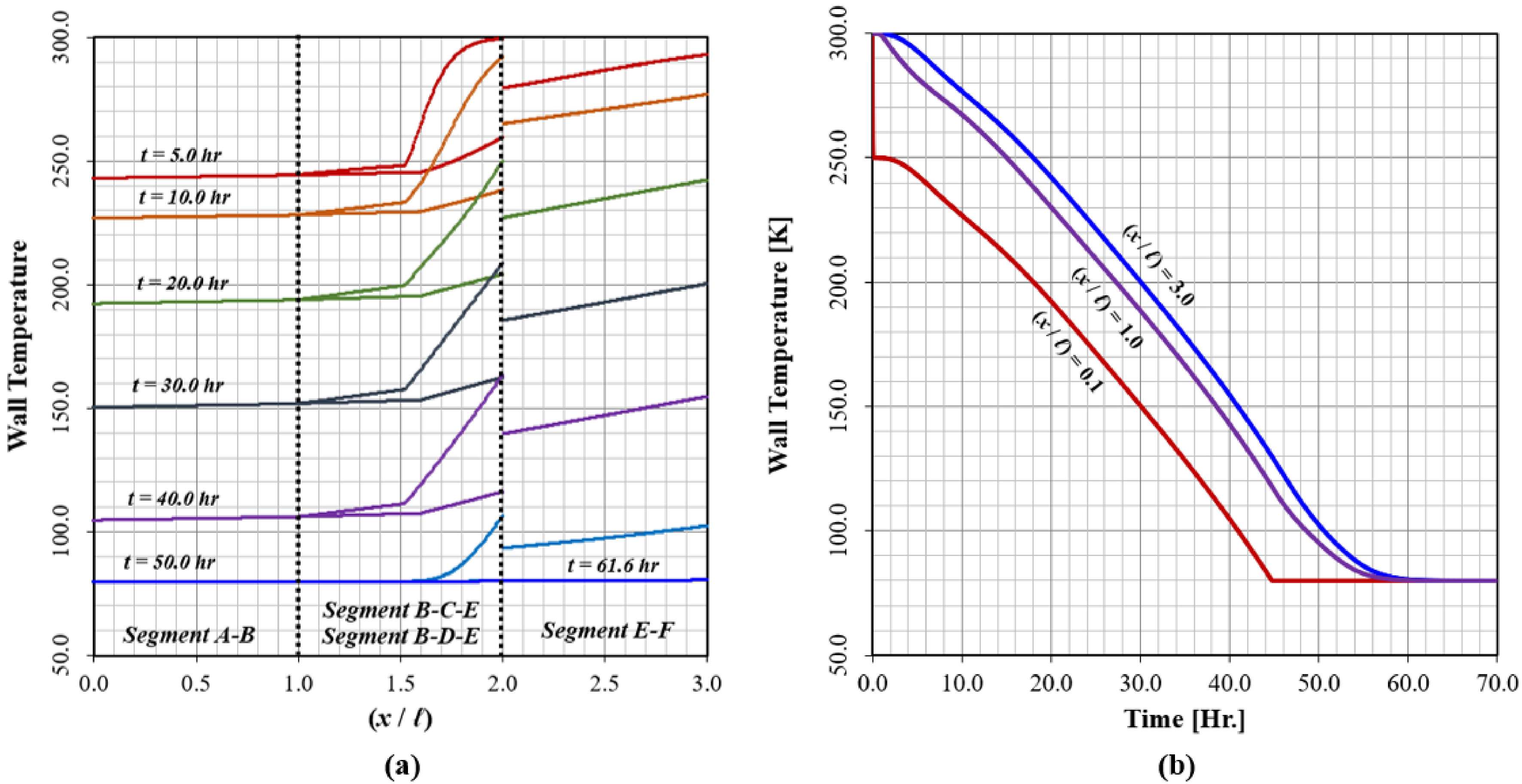
Cool-Down of FRIB LINAC Segment Cryogenic Distribution [1]





- Cool-down of FRIB LINAC segment 2 cryogenic transfer line
  - Constant supply mass flow rate (10.0 g/s)
  - Only the sub-atmospheric circuit is considered for this simulation
  - This circuit has a significant thermal mass in the return section (blue) due to the large sub-atmospheric return header
- To demonstrate the versatility of the model, the mass flow rate (and return pressure at 1.2 bar) is maintained constant
  - Inlet pressure is calculated
  - During the cool-down process, the mass flow rate is maintained constant by adjusting the valve flow coefficient

Cool-Down of FRIB LINAC Segment Cryogenic Distribution [2]



Calculated (a) spatial and (b) temporal distribution of pipe wall temperature (T_W) for FRIB LINAC segment 2 cryogenic transfer line (section A-B-C-D-E-F with both branches, sub-atmospheric circuit)

Summary

- A one-dimensional transient numerical model for estimating the cool-down process of cryogenic transfer lines at FRIB was developed
- Solves spatio-temporal distribution of fluid pressure, mass flow rate, and fluid / pipe wall temperature
  - Flexible to accommodate a variety of transfer line arrangements, boundary conditions, and different input parameters
- Validated with a closed form analytical solution and measurements during actual cool-down of a cryogenic transfer line at FRIB
- Cool-down of two different cryogenic transfer lines at FRIB was simulated
- Useful as a predictive tool
- Future work
  - Investigating different convective heat transfer correlations to better match the measurements
  - Appropriate equations to predict the thermal radiation heat in-leak
  - Further modularizing the code so it is more easily modifiable

Acknowledgement

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