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

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

<table>
<thead>
<tr>
<th>Section</th>
<th>Line Size (NPS)</th>
<th>Length [m]</th>
<th>Piping Components</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exp. Jnt</td>
</tr>
<tr>
<td>A-B</td>
<td>1.5</td>
<td>54.5</td>
<td>9</td>
</tr>
<tr>
<td>B-C</td>
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<tr>
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<td>C-D (Br 2)</td>
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<td>D-E</td>
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</tr>
<tr>
<td>E-F</td>
<td>1.5</td>
<td>54.5</td>
<td>9</td>
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</tbody>
</table>
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]

#### Diagram

![Diagram of FRIB LINAC Segment 2](image)

<table>
<thead>
<tr>
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</tr>
<tr>
<td>A-B</td>
<td>1.5</td>
<td>56.0</td>
<td>4</td>
</tr>
<tr>
<td>B-C (Br 1)</td>
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<tr>
<td>C-E (Br 1)</td>
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<tr>
<td>B-D (Br 2)</td>
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<td>D-E (Br 2)</td>
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<tr>
<td>E-F</td>
<td>10</td>
<td>56.0</td>
<td>4</td>
</tr>
</tbody>
</table>
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)
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
The transient temperatures in the fluid and pipe wall are calculated by solving the conservation of energy equations:

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

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

- 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
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.
The thermal model was validated using a closed-form analytical solution.

A simple pipeline is considered for this validation:

- 55.0 m long pipeline
  - \( d_o = 48.26 \text{ mm}, t = 2.77 \text{ mm} \)
- Cool-down from 300 K to 200 K
- 200 K helium gas (5.0 g/s)
Cool-down of FRIB experimental system cryogenic transfer line (A-B-E-F) shield circuit is considered
- consists of an additional copper shield \((d_0 \sim 0.3 \text{ m}, t \sim 1.6 \text{ mm})\) clamped to the segment E-F \((\text{at } x/l = 0.5-1.0)\) and surrounding the rest of the pipes

Cool-down is performed with gaseous helium (maintained constant \( \sim 4.7 \text{ g/s} \))

This phase of cool-down is carried out with a temperature differential of \(50 \text{ K}\), until the entire pipeline reaches \(80 \text{ K}\)

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 \(35 \text{ K} / 4.5 \text{ K}\) 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.
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
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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