Fermilab

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Advancing 1D thermo-hydraulic tools for large cryogenic facilities

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Overview

- Introduction
- The Cryotoolbox Library
  - The existing library
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  - Heat functions
- Examples
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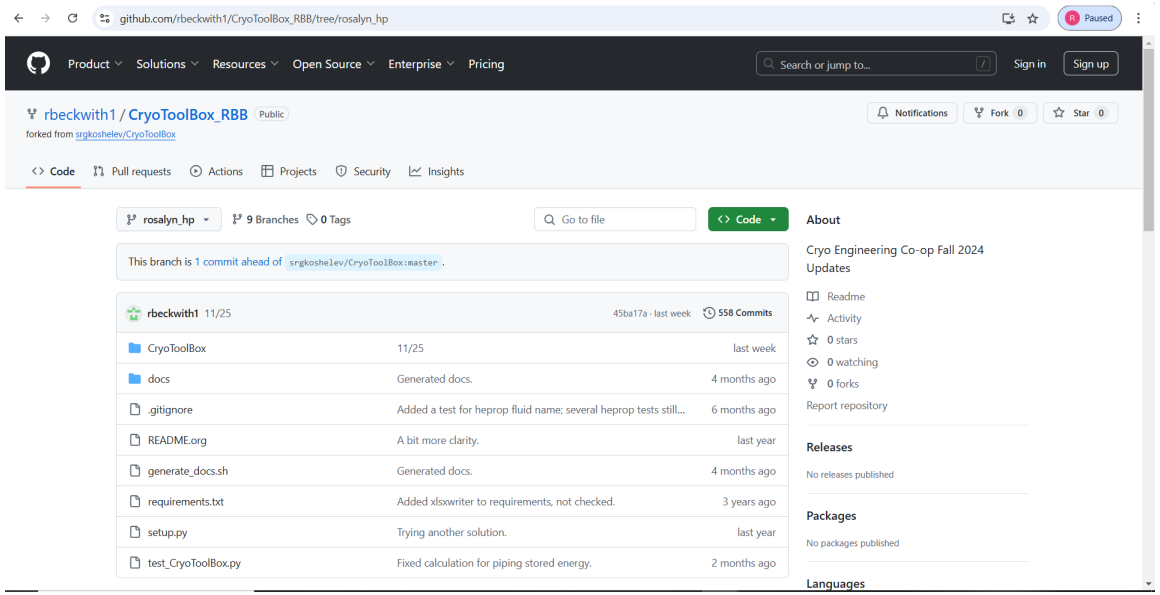
- Conclusion

Introduction

Goal: Create a Thermo-Hydraulic python library that help to **design** and **evaluate** cryogenic system

- Temperature and pressure evolution in large system (accounts for components such as elbows, tees, valves, etc.)
- Automatic unit conversions with PINT
- Link with Coolprop, Refprop, Hepak (Software license required)
- Accounts for standard material inputs (NIST) or accommodates manual input of material properties
- Fast method to verify flow system



CryotoolBox library posted in Github

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The CryotoolBox library

The existing library

Friction Factor Calculations:

- Modified Churchill Formula:
  - Single-step approximation for all flow regimes
- Serghide method:
  - Semi-iterative solution | explicit approximation
  - Full range of turbulent flow | (Crane TP-410 2013)
- Nellis and Klein method (new):
  - Zigrang-Sylvester Correlation for turbulent flow
  - Recommended for $4000 \leq \mathrm{R_e} \leq 10^8$ and

$$10^{-5} \leq \frac{\varepsilon}{\mathrm{D}} \leq 5 \times 10^{-2}$$

Friction factor comparison:

Author	Reynolds number	Relative roughness	$Errmax(\Delta f/f)\%$
Moody	$4000 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 10^{-2}$	$\Delta f/f = 12.08\%$
Altshul	$4000 \leq \boldsymbol{R_e} \leq 10^7$	$0 \leq \boldsymbol{\varepsilon/D} \leq 10^{-2}$	$\Delta f/f > 100\%$
Wood	$R_e > 4000$	$0 \leq \varepsilon/D \leq 5.10^{-2}$	$\Delta f/f = 28.23\%$
Eck	not found	not found	$\Delta f/f = 10.7\%$
Swamee and Jain	$5000 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 10^{-2}$	$\Delta f/f = 2.81\%$
Jain	$5000 \leq R_e \leq 10^7$	$4.10^{-5} \leq \varepsilon/D \leq 5.10^{-2}$	$\Delta f/f = 2.83\%$
Churchill	not found	not found	$\Delta f/f = 4.59\%$
Chen	$4000 \leq R_e \leq 4 \cdot 10^8$	$10^{-7} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 36.18\%$
Shacham	$4000 \leq R_e \leq 4 \cdot 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.88\%$
Round	$4000 \leq R_e \leq 10^7$	$0 \leq \varepsilon/D \leq 10^{-2}$	$\Delta f/f = 7.85\%$
Barr	$2300 \leq \boldsymbol{R_e} \leq 10^8$	$0 \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f = 86.95\%$
Zigrang - Sylvester	$4000 \leq R_e \leq 10^8$	$10^{-5} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.17\%$
Haaland	$4.10^3 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 1.41\%$
Serghides	$2300 \leq \boldsymbol{R_e} \leq 10^8$	$10^{-6} \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f \gg 100\%$
Tsal	$4.10^3 \leq \boldsymbol{R_e} \leq 10^8$	$0 \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f > 100\%$
Manadilli	$5.235 \cdot 10^3 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5.10^{-2}$	$\Delta f/f = 2.5\%$
Romeo	$3 \times 10^3 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.16\%$
Achour (2002)	$R_e \geq 10^4$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 2\%$
Ajinkya	$4x10^4 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 7\%$
Buzzelli	$2300 \leq \boldsymbol{R_e} \leq 10^8$	$0 \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f \gg 100\%$
Sonnad	$4000 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 5.32\%$
Rao	$2300 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 8.879\%$
Avçi	$2300 \leq \boldsymbol{R_e} \leq 10^8$	$0 \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f \gg 100\%$
Vatankhah 2009	$10^4 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 10^{-2}$	$\Delta f/f = 0.16\%$
Papaevangelou	$4000 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.76\%$
Brkić	$4000 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 2.13\%$
Fang	$3000 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.54\%$
Ghanbari	$2300 \leq \boldsymbol{R_e} \leq 10^8$	$0 \leq \boldsymbol{\varepsilon/D} \leq 5 \cdot 10^{-2}$	$\Delta f/f = 88.02\%$
Brkić 2011a	$2300 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 3.46\%$
Samadianfard	$4000 \leq Re \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 6.31\%$
Achour 2012	$2300 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.366\%$
Cojbasic	$2300 \leq R_e \leq 10^8$	$0 \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.18\%$
Vatankhah 2014	$4000 \leq R_e \leq 10^8$	$10^{-6} \leq \varepsilon/D \leq 5 \cdot 10^{-2}$	$\Delta f/f = 0.146\%$

Zeghadnia, L., Robert, J., & Achour, B. (2019). *"Explicit solutions for turbulent flow friction factor: A review, assessment and approaches classification."*

The existing library

Pressure drop calculations:

- Incompressible method:
  - Valid for incompressible flow or for direct inputs (known K value)
  - Reasonable approximation for compressible flow when pressure drop <10% inlet pressure
- Two methods for compressible flow:
  - Isothermal and compressible flow | iterative method
  - Adiabatic method | Derived from nozzle equations

$$dP = \frac{1}{2} K \rho v^2$$

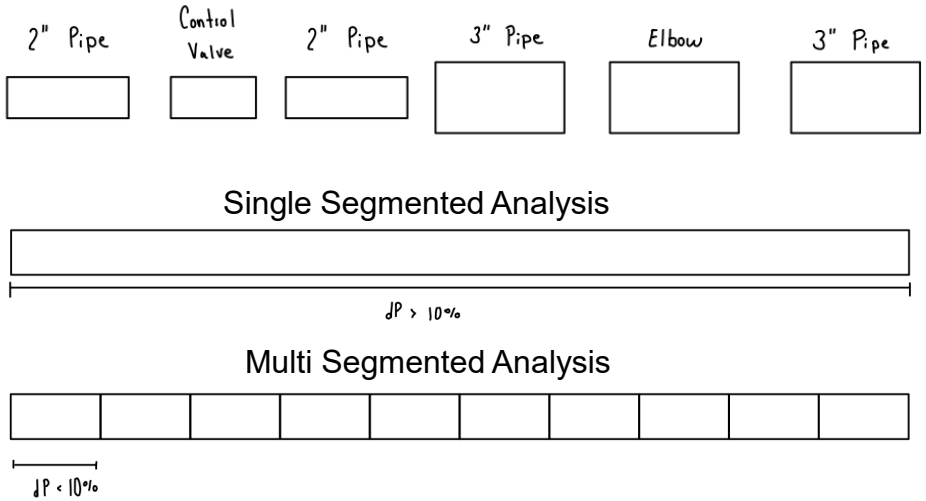
$$P_1^2 - P_2^2 = \frac{\dot{m}^2 RT}{A^2}\left(2\ln\frac{P_1}{P_2} + f\frac{L}{D}\right)$$

$$\frac{P_1}{P_2} = \frac{M_2}{M_1}\sqrt{\frac{1+M_2^2(\gamma-1)/2}{1+M_1^2(\gamma-1)/2}},$$

Segmented strategy (Line function):

- Function to connect components into one system
- Used for a more accurate pressure drop calculation

  (<10% incompressible approximation)



Heat transfer coefficients

- Internal convection:

(Nusselt Number for forced convection)

  - Laminar flow - Bennet, T.D., Journal of Heat Transfer
  - Turbulent flow - Nellis and Klein (2020)
- External convection:
  - Natural convection (Churchill Nusselt correlation for cylindrical shape)
  - Forced convection
- Multi Layer Insulation correlation:
  - Modified Lockheed Equation
- Radiative heat transfer
- Icing model (see next slide)
- Conduction in components (NIST data)

$$k = \frac{1}{\Delta T}\int_{T_1}^{T_2} k(T)\, dT$$

Turbulent flow Nusselt number:

$$N_{u_{D_h,fd}} = \frac{\left(\frac{f_{fd}}{8}\right)(Re_{D_h} - 1000)Pr}{1 + 12.7\left(Pr^{2/3} - 1\right)\sqrt{\frac{f_{fd}}{8}}} \quad \text{for } 0.5 < Pr < 2000 \text{ and } 2300 < Re_{D_h} < 5 \times 10^6$$

Nusselt for natural convection:

$$Nu_{air}(OD_{pipe}, T_S) := \left[0.6 + \frac{0.387 \cdot Ra_{air}(OD_{pipe}, T_S)^{\frac{1}{6}}}{\left[1 + \left(\frac{0.559}{Pr_{air}(T_{film}(T_S))}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2 \quad HTC_{air}(OD_{pipe}, T_S) := \frac{Nu_{air}(OD_{pipe}, T_S) \cdot k_{air}(T_{film}(T_S))}{OD_{pipe}}$$

MLI equation:

$$q_{total} = \frac{C_R\, \varepsilon\, (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_S\, \bar{N}^{2.63}(T_h - T_c)(T_h + T_c)}{2\,(N+1)} + \frac{C_G\, P\, (T_h^{0.52} - T_c^{0.52})}{N}$$

MLI Coefficients:

Materials	Coefficients		
	C_R	C_S	C_G
Unperforated DAM with Silk-net [7]	5.39×10^{-10}	8.95×10^{-8}	1.46×10^{-4}
Perforated DAM with Glass-tissue [32]	7.07×10^{-10}	7.30×10^{-8}	1.46×10^{-4}
Perforated DAM with Dacron [32]	4.94×10^{-10}	Shown in (4.1)	1.46×10^{-4}

Heat transfer coefficients

- Icing method:
  - Calculate the modified heat transfer coefficient on the external surface of a pipe
  - Applicable for relief pipe (fast event)
  - Neglects ice thickness
  - For the radiative heat transfer, assume $\epsilon_{ice} = 0.96$ when surface < 273 K
  - Use Lewis Number and Lewis Relationship (Bergman and Lavine 2017)

Mass flux and heat flux relationship:

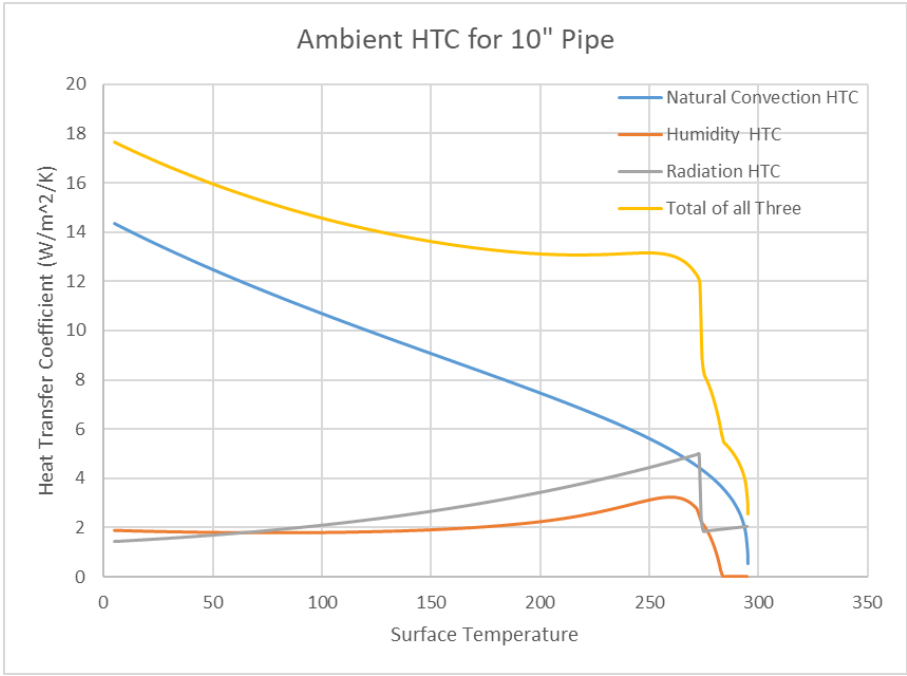
$$Mass\ flux_{condensation} = h_{convection} * Lewis_{Relationship} * \Delta Concentration$$

$$Heat\ flux_{condensation} = Mass\ flux_{condensation} * \Delta Enthalpy$$

Utilizes mass and heat transport correlations with the Lewis number (ratio of thermal and mass diffusivities)

$$Lewis_{Number} = \frac{Schmidt}{Prandtl} \quad \& \quad Lewis_{Relationship} = \frac{Lewis\ Number^{-\frac{2}{3}}}{\rho * C_p}$$

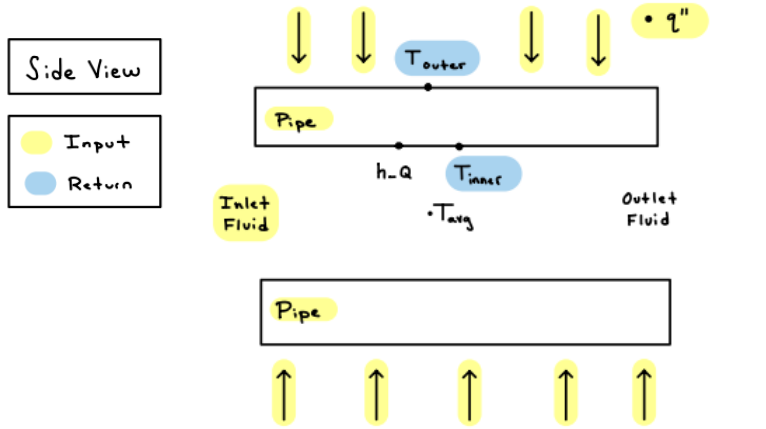
Heat transfer comparison for a 10” pipe:



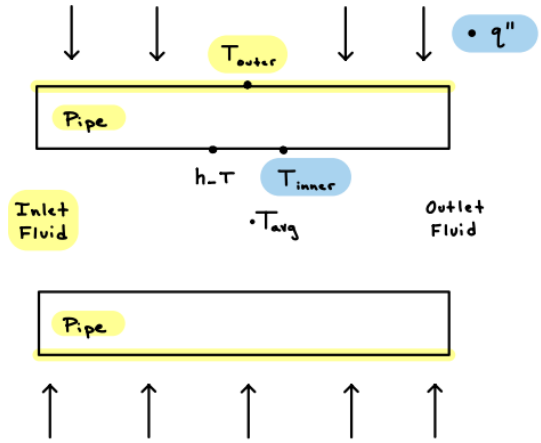
Heat functions

Several functions have been created to automatically calculate the pressure and temperature evolution in flow components under various heating conditions

- **Constant heat load**:
  - Calculate the pressure drop
  - Calculate the outlet flow conditions (Enthalpy)
  - Fluid temperature = average of inlet and outlet
  - Find inner wall temp : $T_{inner} = \frac{q^{"}}{h_Q * S_i} + T_{average}$
  - Calculate outer wall temperature



- **Constant wall temperature** (iterative method):
  - First loop: average fluid temp = inlet temp
  - Calculate inner wall temperature
  - Calculate outlet flow conditions
  - Iterate with new value



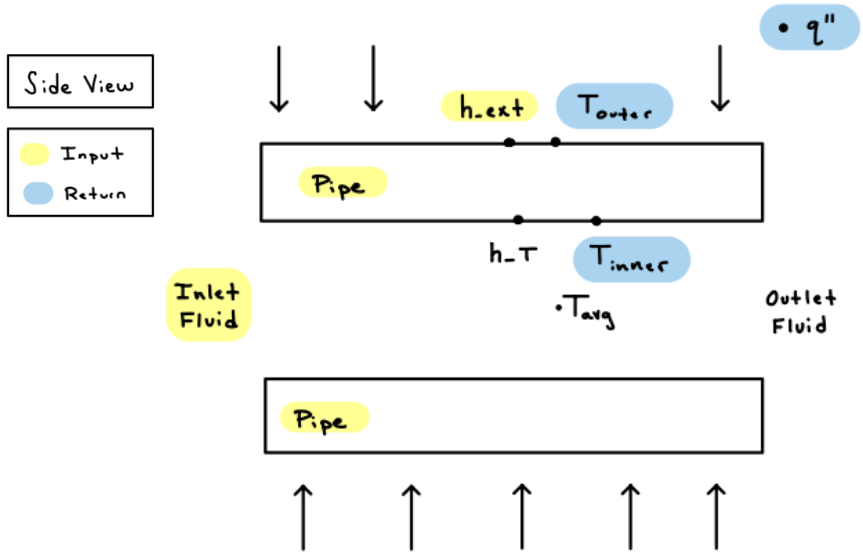
Heat functions

- **Constant external heat transfer coefficient**:
  - Calculate outer wall temperature with external convection
  - Calculate inner wall temperature with convection equations

$$T_{inner\ wall} = \left(\frac{h_{external}}{h_T}\right) * \left(\frac{D_o}{D_i}\right) * (T_{external} - T_{outer\ wall}) + T_{average}$$

  - Calculate enthalpy change
  - Calculate outlet flow conditions
  - Recalculate average temperature and iterate

- **This Function can use variable heat transfer coefficient (natural convection, icing,)**



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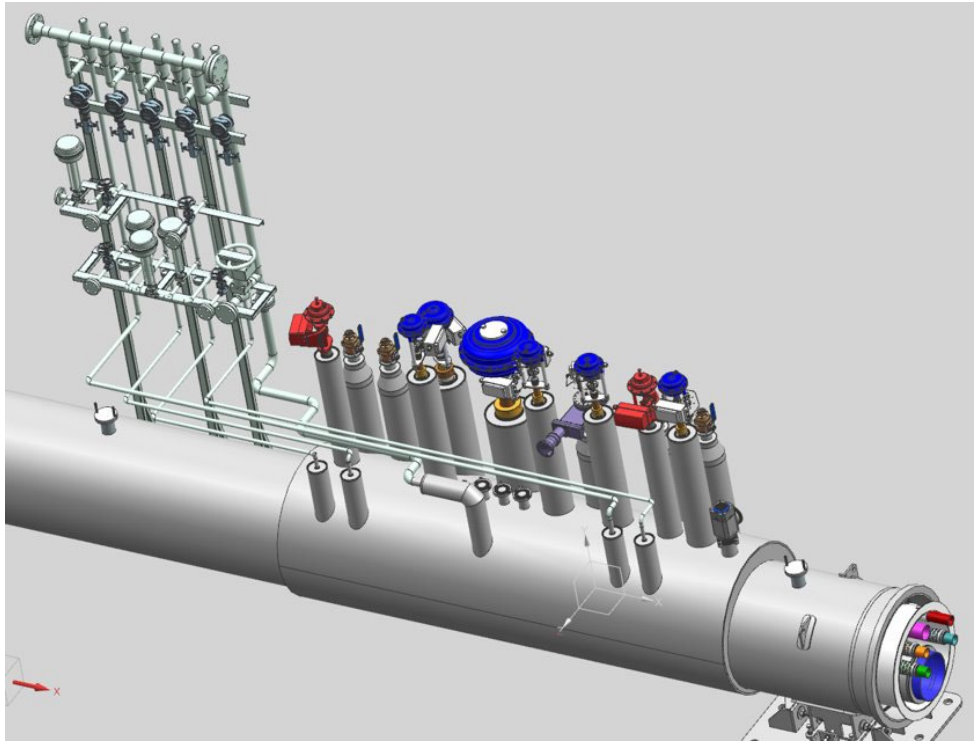
Examples

PIP-II Bayonet Can Relief Pressure Drop

- Model pressure drop on relief piping:
  - Internal pipe, before the relief valve
  - External pipe, after the relief valve, modeling different heated scenarios
- Results validate design geometry & provide values for analysis required by API 520 7.3.6 showing system is protected from instability



PIP-II Bayonet Can Relief Pressure Drop

Different heated scenarios:

- Defined outer wall temperatures – overpressure at the beginning of the relief
- Defined heat transfer coefficients
- Defined heat flux

Summary of Results for one relief line DN40:

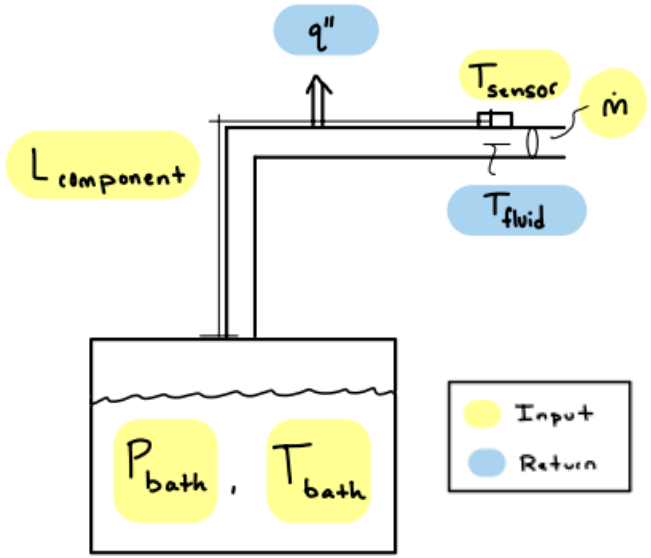
Inlet Parameters:											
mass flow rate	g/s	258									
P inlet (for internal piping)	bar	29.04									
P inlet (for external piping)	bar	28.15									
T inlet	K	40									
3% Pressure Drop	mbar	720									
		No Applied Heat	Defined Outer Wall Temperature			Defined External Heat Transfer Coefficient			Defined Applied Heat Flux		
			293K	250K	200K	1 W/(K*m^2)	5 W/(K*m^2)	10 W/(K*m^2)	500 W/m^2	1000 W/m^2	10000 W/m^2
Parameter	Unit										
dP (external piping)	mbar	610.4	2840.2	2350.9	1812.2	611.2	614.5	618.5	611.8	613.1	637.7
Outlet Temp	K	40	249.7	209.4	163.5	40.1	40.6	41.1	40.2	40.4	43.8
Inner Wall Temp Range	K	40-40	103-263.8	85.2-222	65.6-174	40-40.1	40.1-40.6	40.2-40.3	40-40.2	40.1-40.5	41-44.6
Outer Wall Temp Range	K	40-40	293-293	250-250	200-200	40.1-40.2	40.7-41.3	41.4-42.5	40.3-40.5	40.6-40.9	45.5-48.8
Heat Flux Range on Each Component	W/m^2	0-0	1110000-223000	987000-197000	721000-165000	300.3-300.2	1498-1495	2988-2975	500-500	1000-1000	10000-10000

Heat Load on Sub-atmospheric lines

Goal: More realistic calculation for the temperature of the fluid and corresponding heat flux in sub-atmospheric transfer lines

Hypothesis:

- Assume a uniform heat flux imposed on each components of the line
- Assume heat transfer coefficient in straight pipes



Methodology (iterative method):

1. Calculate the wall heat flux on the system assuming fluid temperature = sensor temperature
2. Calculate the outer wall temperature on each component
3. Converge to a solution for the heat flux that correlates to when outer wall temperature at the sensor location = sensor temperature

Heat Load on Sub-atmospheric lines

- This model is particularly applicable for sub-atmospheric line in particle accelerators like LCLS-II, PIP-II
- The low pressure and high temperature flow leads to a large dT
- Current assumptions lead to highly overestimating the heat load

Estimated Conditions from LCLS-II Sub Atmospheric Line:

- 100 g/s mass flow rate
- 2 K and 0.03 bar
- 10” SCH 10 pipe
- 10 meters pipe split into 20 segments
- Sensor located at 8.25 m (arbitrary)
- Sensor reading 2.1 K (arbitrary)

Results

Previous Model: q” = 8.29 W/m^2

New Model: q” = 1.25 W/m^2

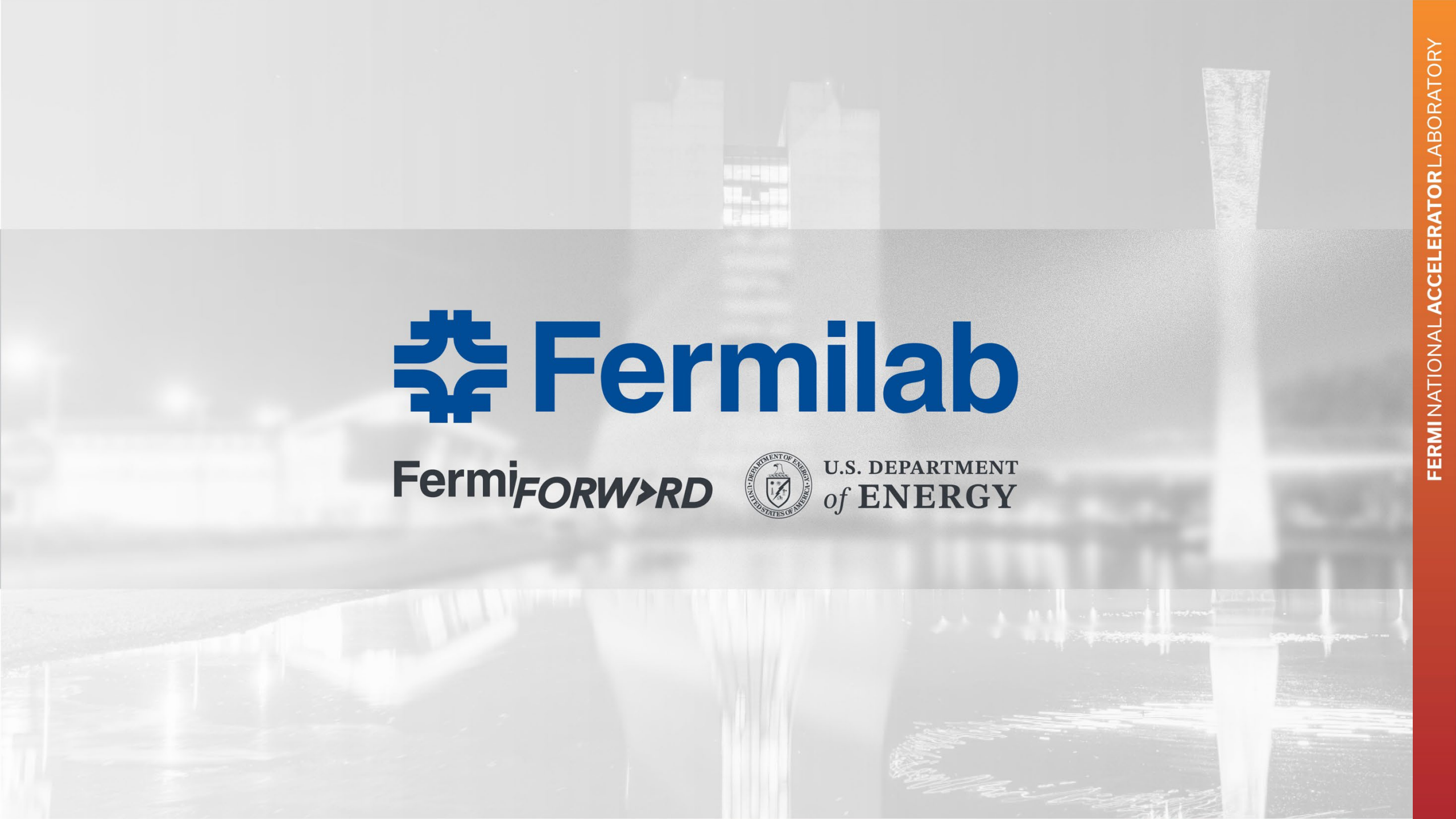
Temp Difference (sensor and fluid) = 0.08557 K

Fluid Temp at Sensor = 2.01 K

Assuming sensor temp = fluid temp led to overestimating the heat load by 6.6X

Conclusion

- Code is useful as a design aid to model flow parameters and pressure drop with various heating condition
- New heat load functions contribute to expand the capabilities of the code for large cryogenic system (including relieving scenario)
- Powerful evaluation tool when combined with python “optimization methods”
- Next phase:
  - Add additional pressure drop calculations: (Rennels method for pressure drop <40%)
  - Improvements to make code more user friendly
  - Add transient analysis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