Multiphase-Tolerant Turbine (MuTT) Development for an sCO_2 PTES System

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Development of a Multiphase-Tolerant Turbine for Pumped Thermal Energy Storage

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U.S. DEPARTMENT OF ENERGY

Award No. DE-EE0009815

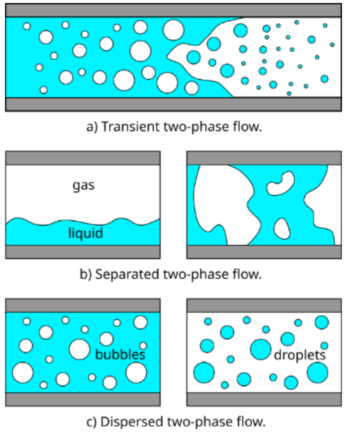
Office of Energy Efficiency and Renewable Energy
under the Solar Energy Technologies Office

Project Partners:
Echogen & Flowserve

ECHOGEN power systems FLOWSERVE

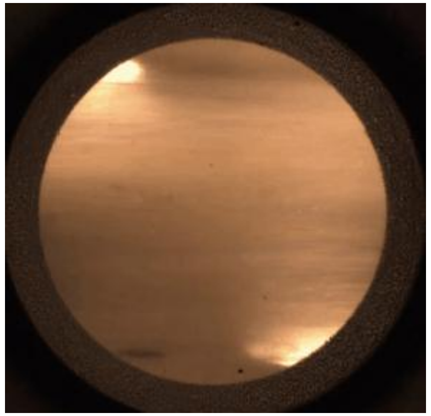
Why is a cold turbine difficult?

- **Multiphase flow**!
- Lack of validation data for loss models in this flow regime [3-5]
- Lack of turbine design experience in the open literature [6-7]



[3]

[6]



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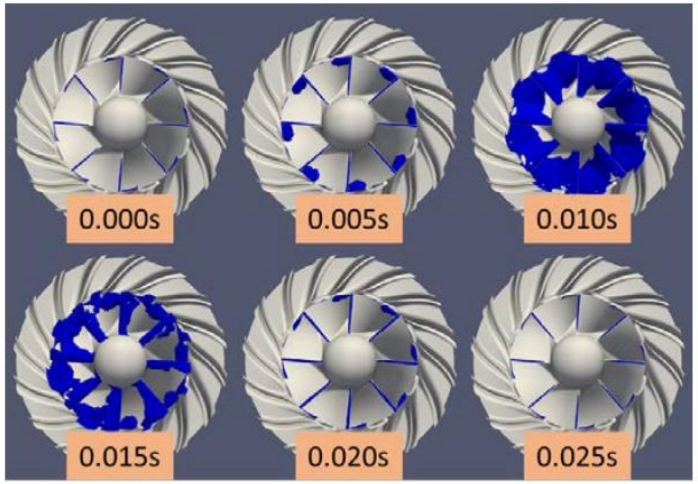
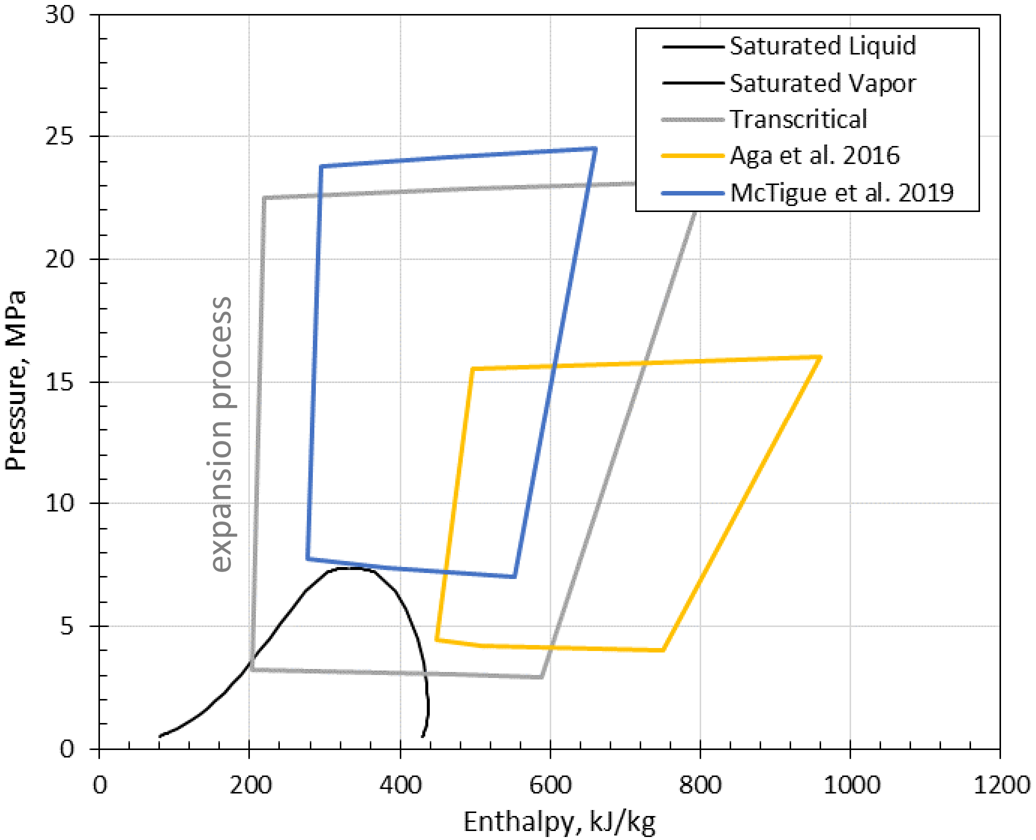


[7]

Various examples of sCO2 heat pumps



Multiphase Tolerant Turbine (MuTT) Project Overview

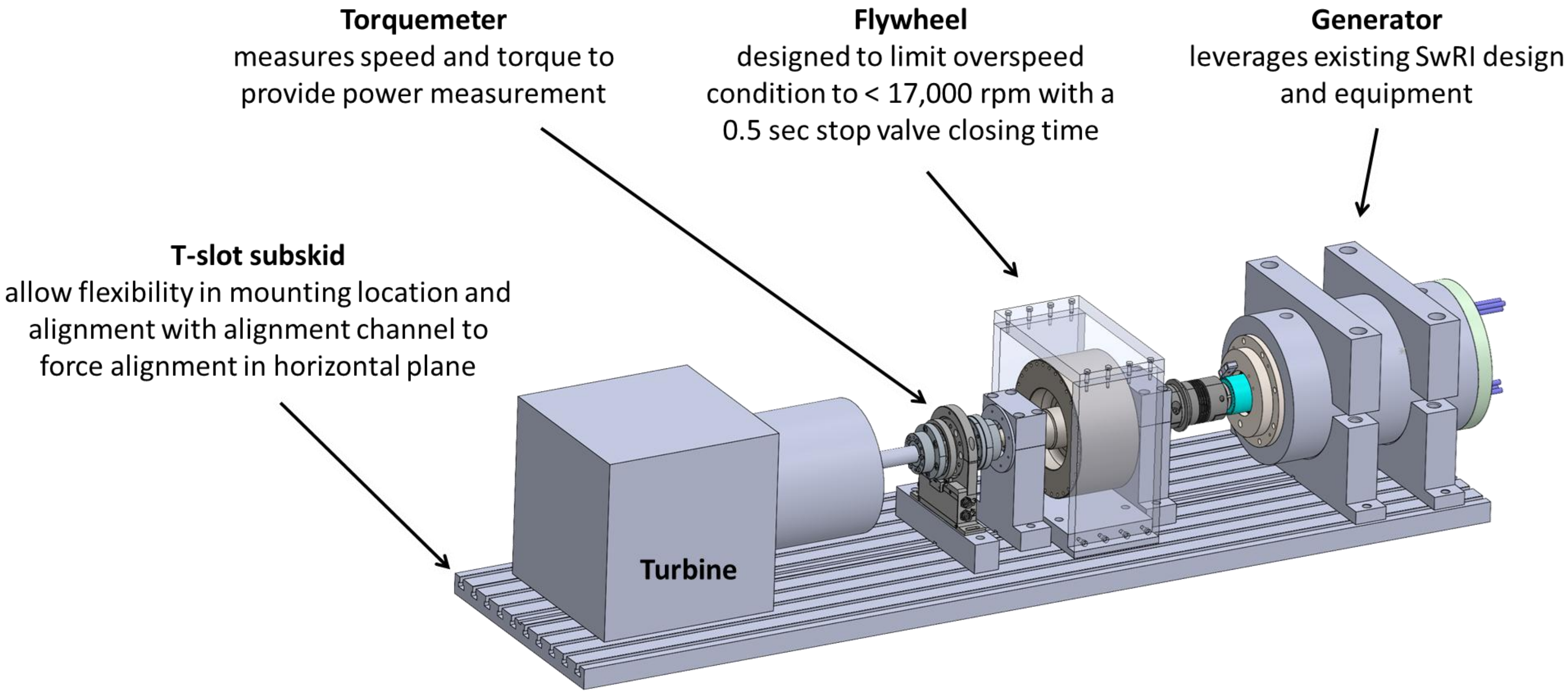
Project Objective:

Retire multiphase turbine design risks through an understanding of multiphase turbine operation, enabling improved turbine performance and operability range

BP1 – Design	BP2 – Procurement & Assembly	BP3 – Testing
1. Turbine design 2. Multiphase CO2 modeling validation data 3. Test loop design	1. Procurement 2. Assembly 3. Commissioning	1. Testing 2. Data processing

Waiting for BP2 approval

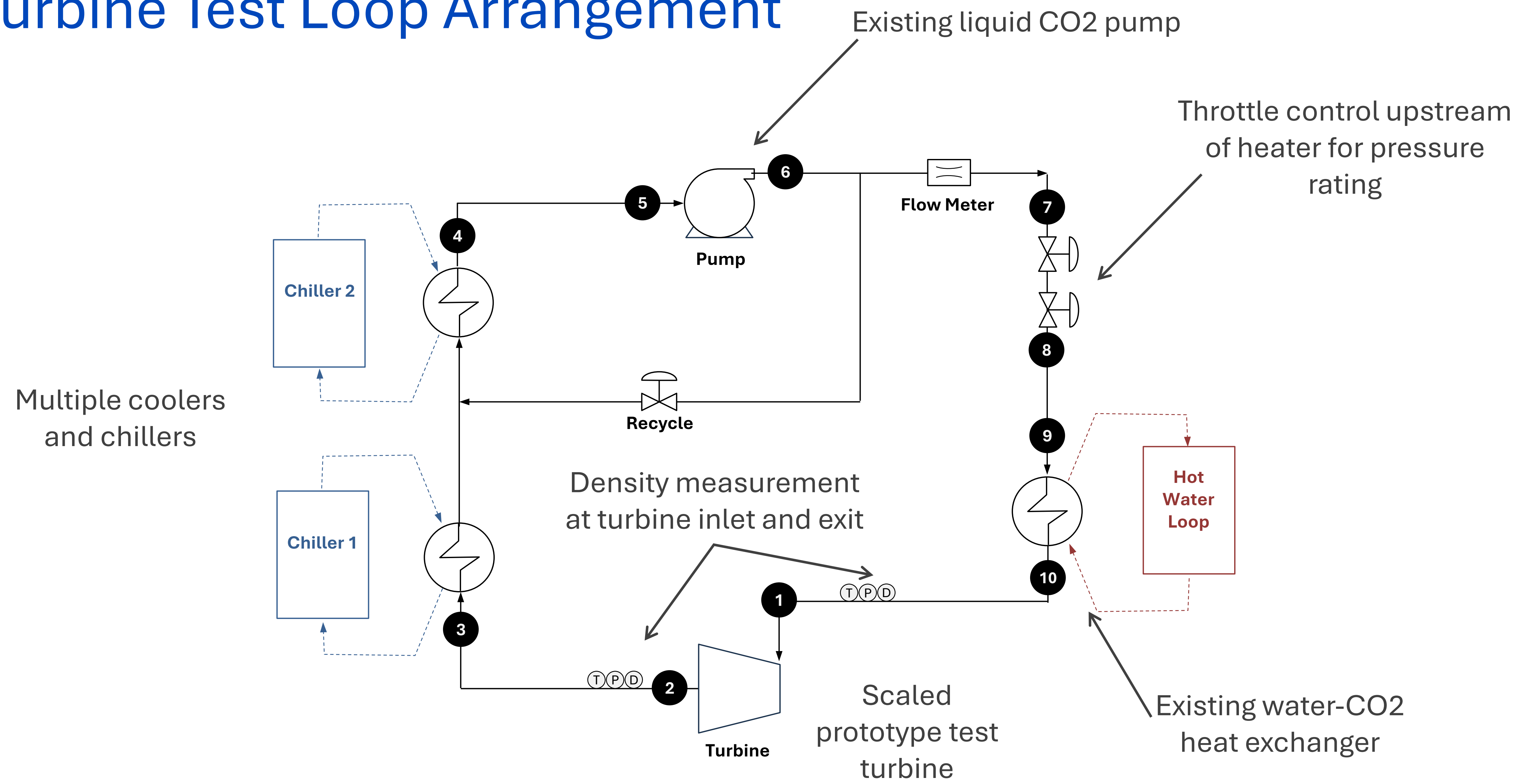
This presentation will highlight our most significant challenge in the loop design & initial multiphase data



For Scaled Turbine Test in BP3

MUTT LOOP DESIGN

Turbine Test Loop Arrangement

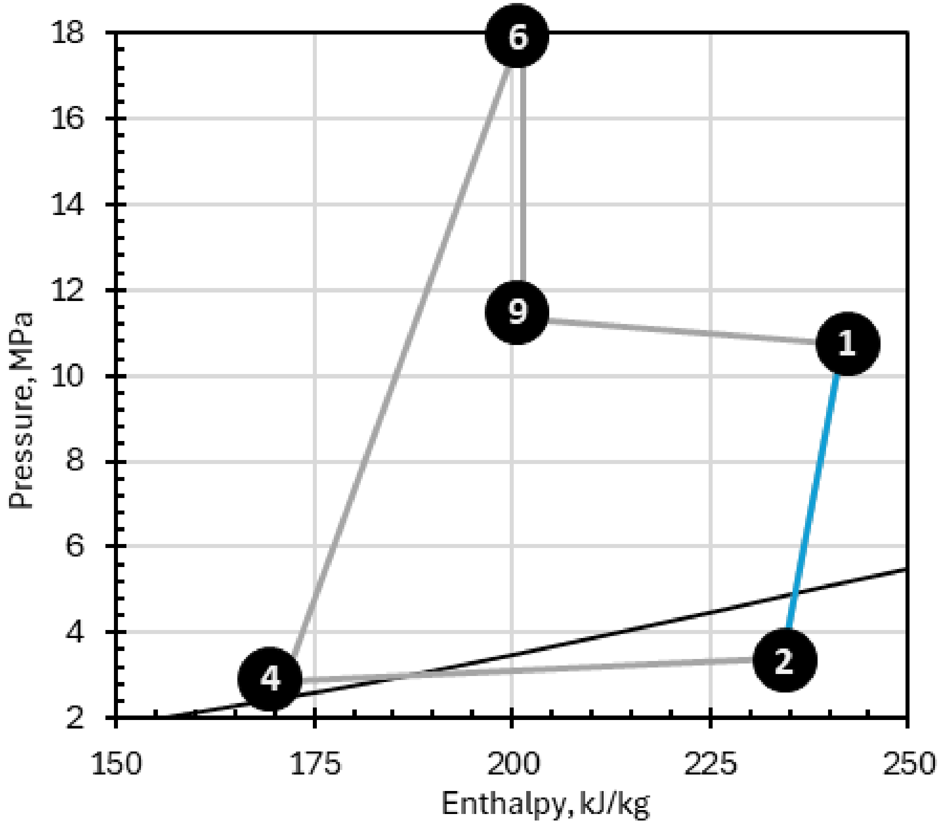


Test Loop Conditions Definition

Two key challenges arose after initial sweeps of test conditions:

1) confidence in pressure loss modeling

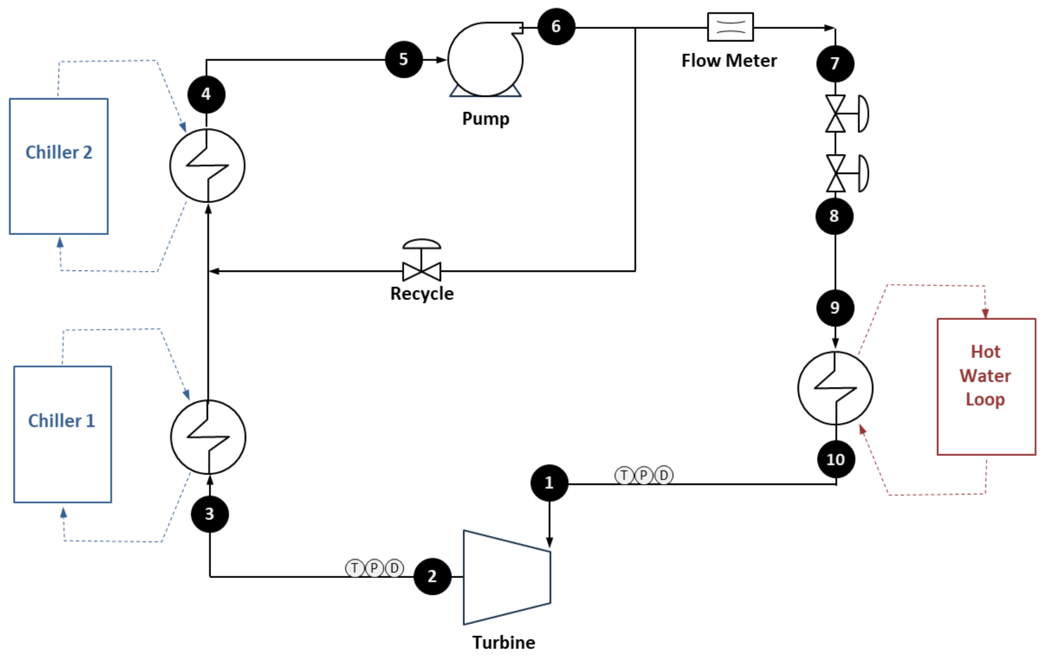
2) the large required thermal duty for heat rejection

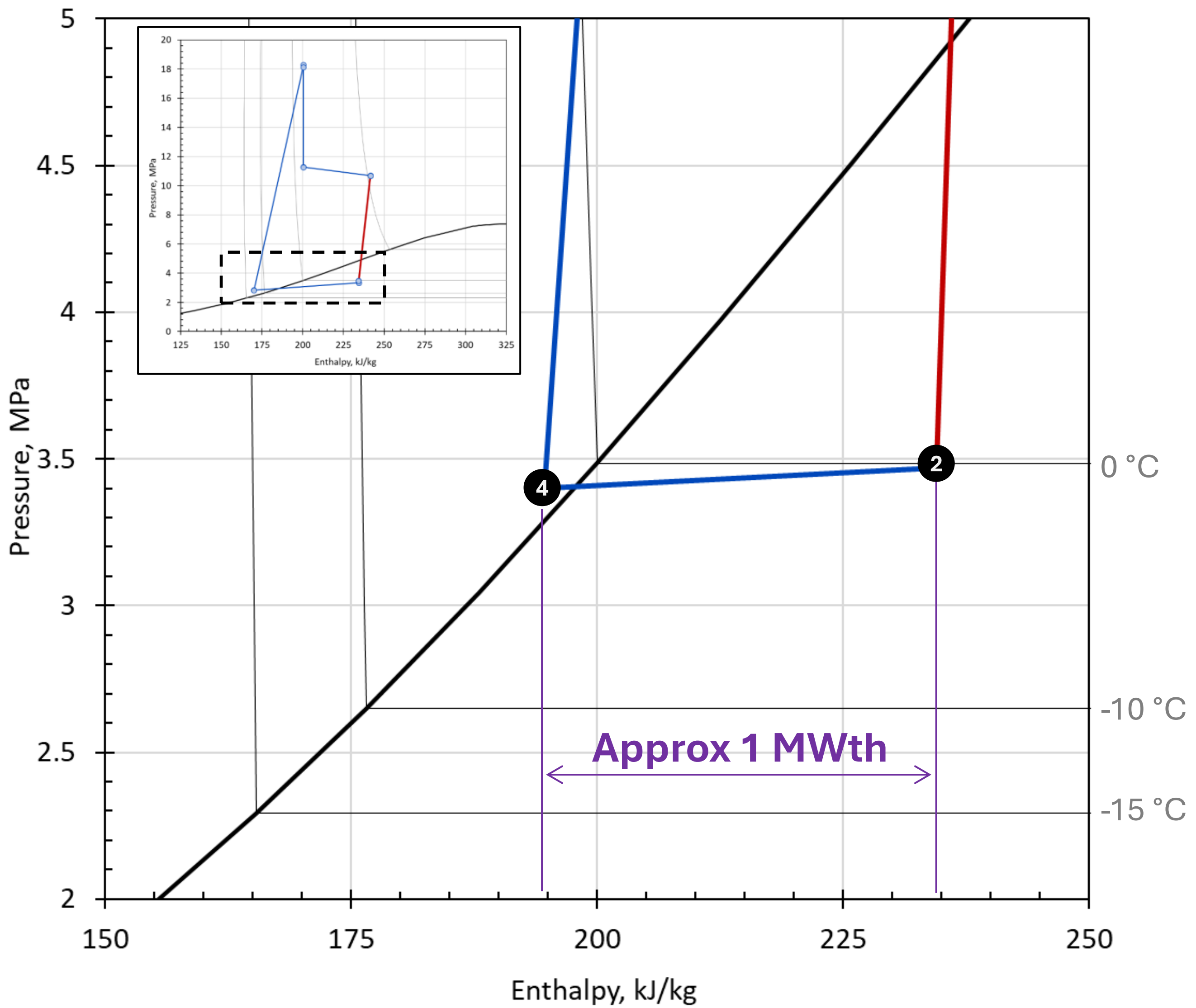


Estimating heat rejection requirement with gross assumptions of pressure losses...

Assume:

1. **Neglect pressure loss in the piping**
2. **Minimal pressure loss through the HX**
3. **No subcooling**

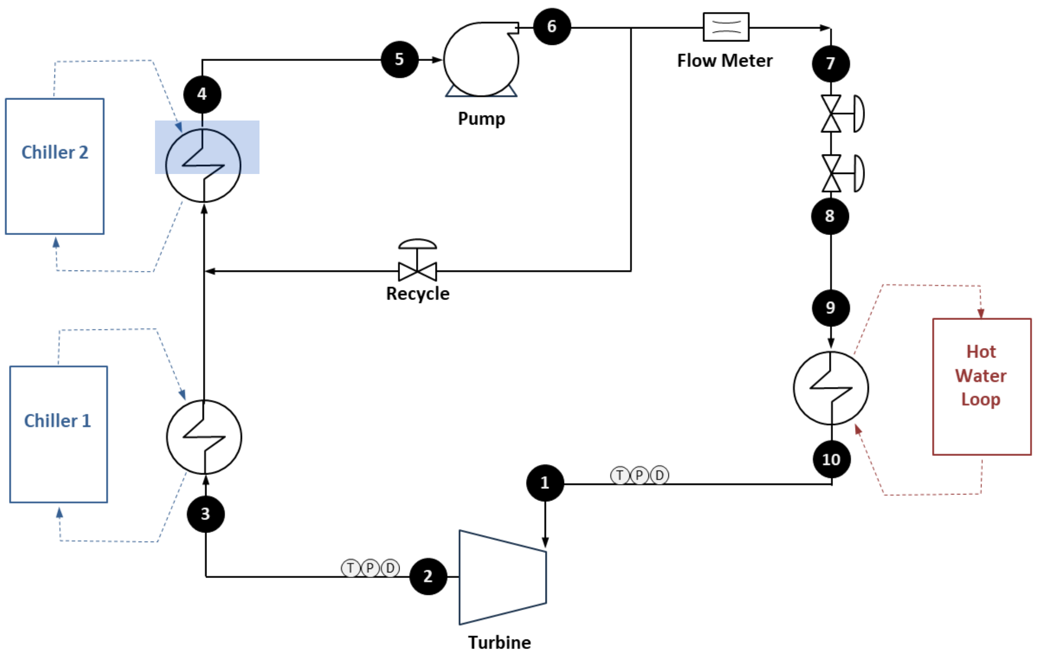


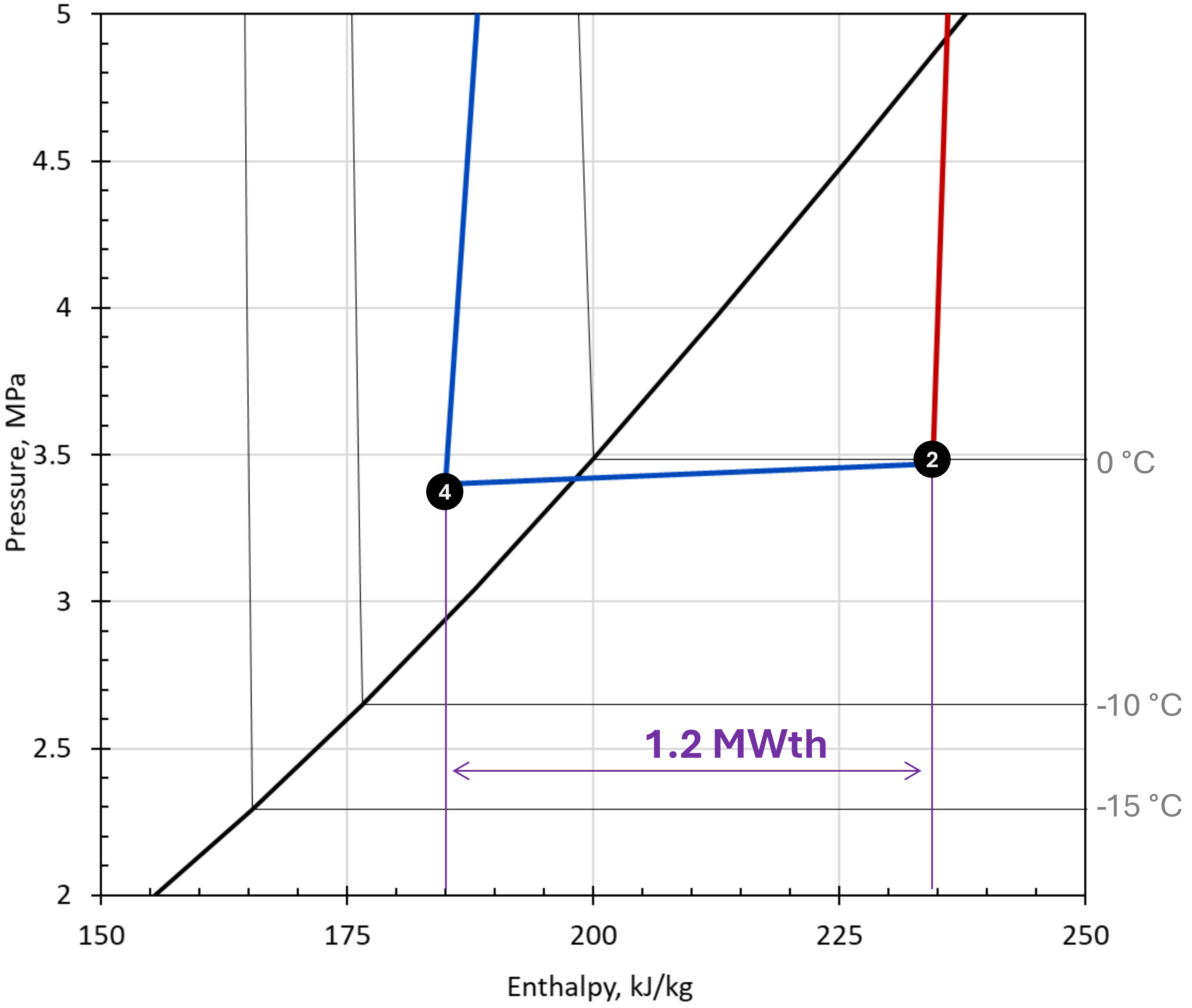


Estimating heat rejection requirement with gross assumptions of pressure losses...

Assume:

1. **Neglect pressure loss in the piping**
2. **Minimal pressure loss through the HX**
3. ~~No subcooling~~ **5 °C subcooling**

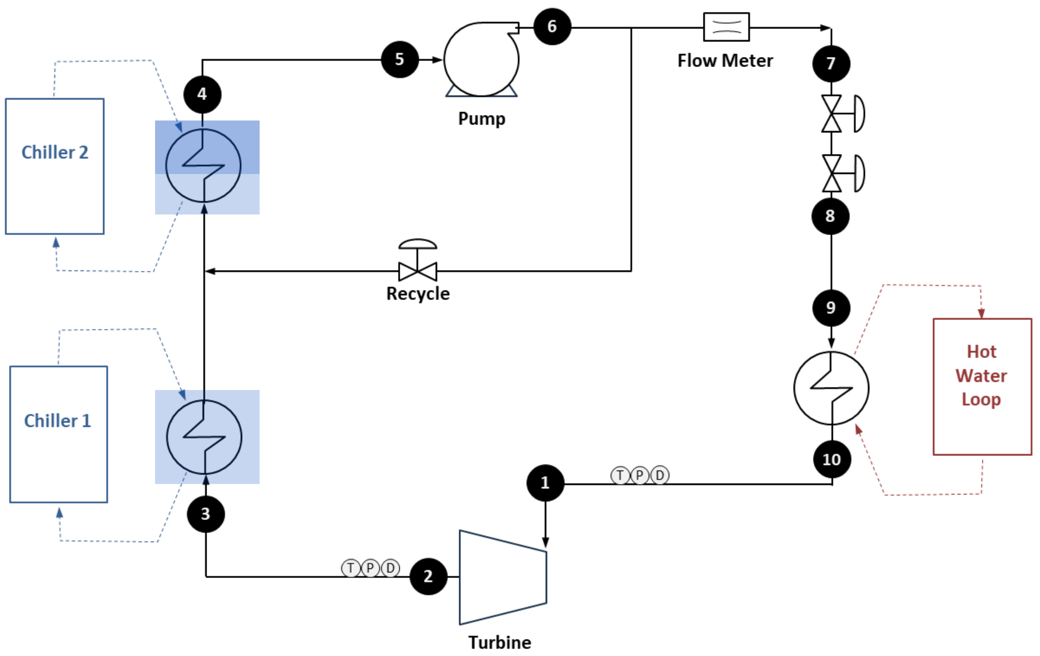


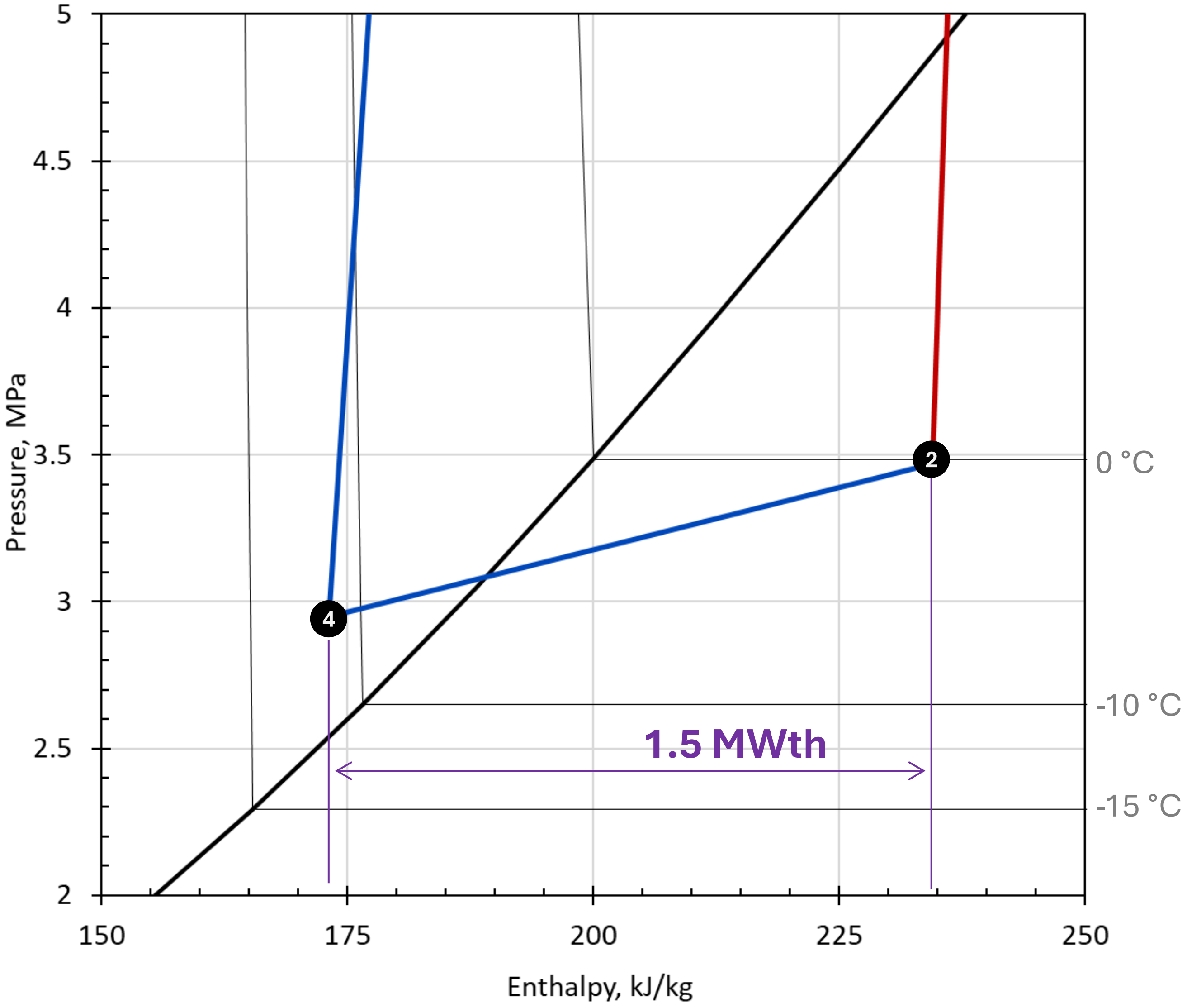


Estimating heat rejection requirement with gross assumptions of pressure losses…

Assume:

1. **Neglect pressure loss in the piping**
2. ~~Minimal~~ **15% pressure loss through the HX**
3. ~~No subcooling~~ **5 °C subcooling**

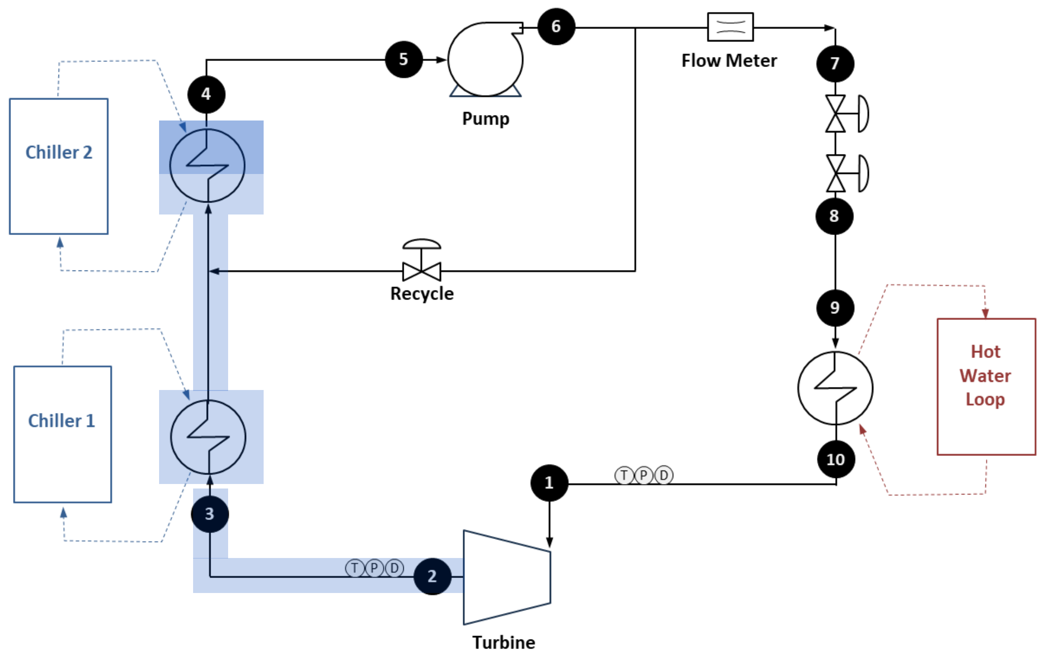


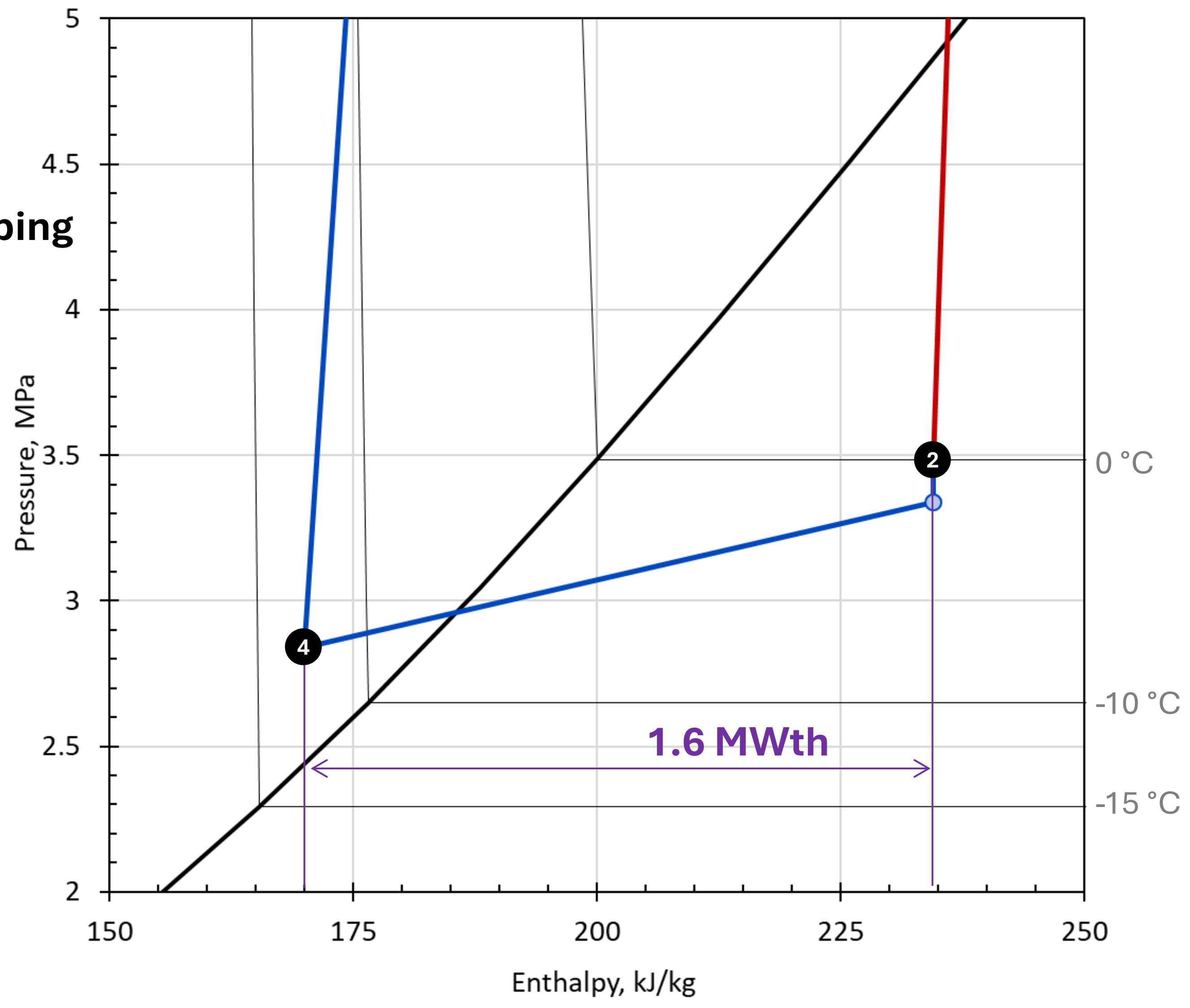


Estimating heat rejection requirement with gross assumptions of pressure losses…

Assume:

1. ~~Neglect~~ **Multiphase pressure loss in the piping**
2. ~~Minimal~~ **15% pressure loss through the HX**
3. ~~No subcooling~~ **5 °C subcooling**





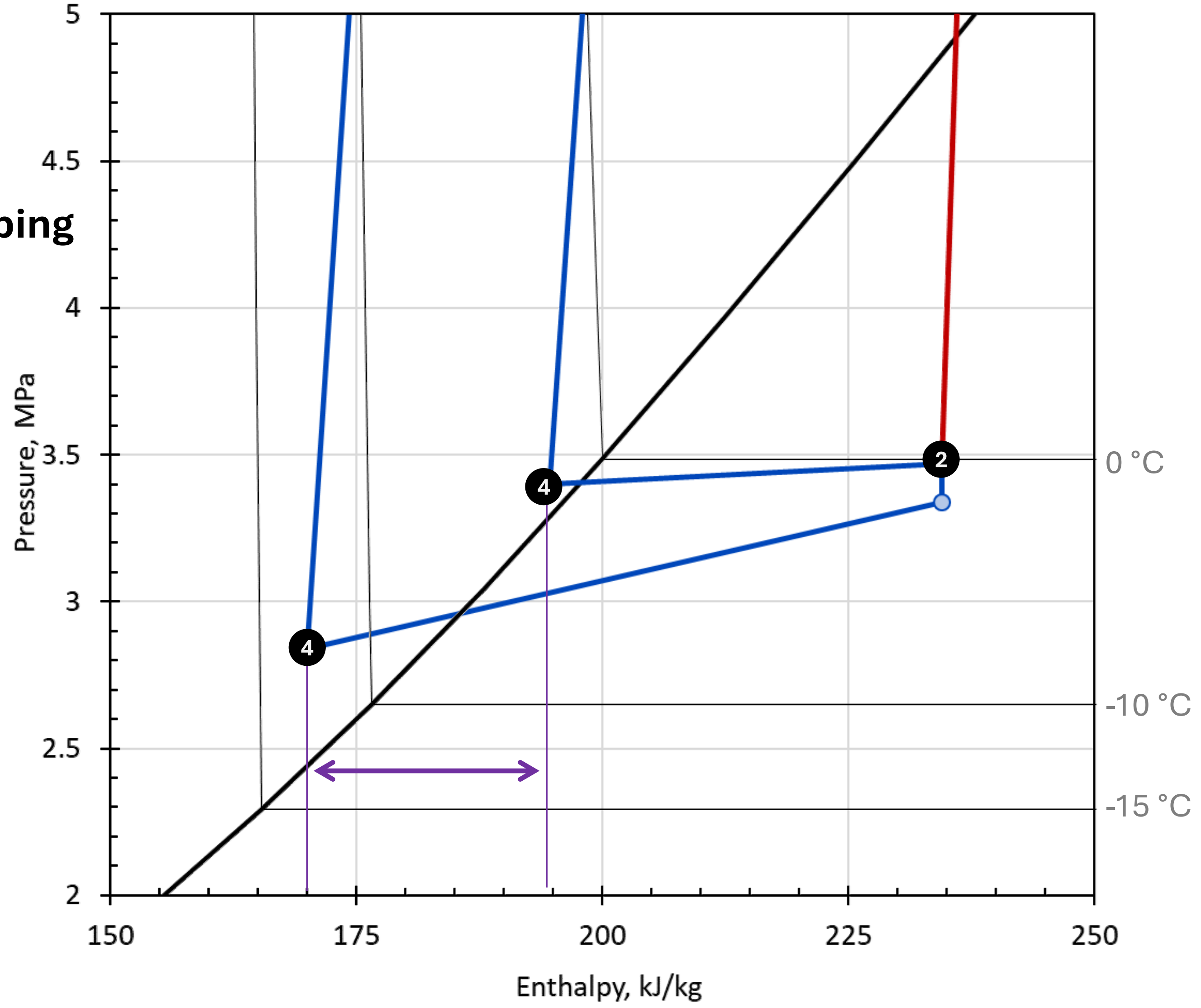
Assumptions of pressure losses underestimated the required cooling duty by 0.6 MWth

Assume:

1. ~~Neglect~~ **Multiphase pressure loss in the piping**
2. ~~Minimal~~ **15% pressure loss through the HX**
3. ~~No subcooling~~ **5 °C subcooling**

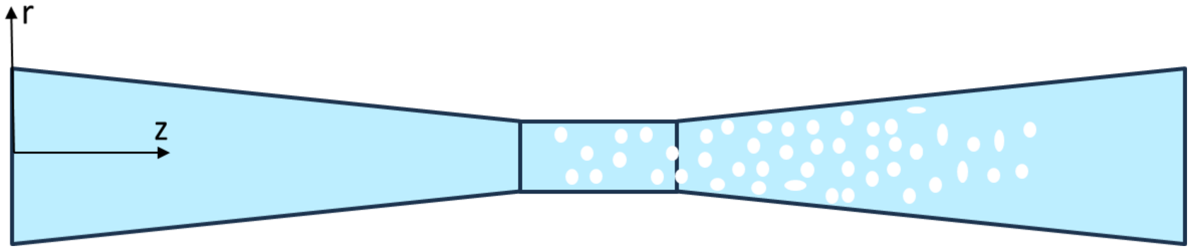
These are all assumptions easily made during proposal and rough order of magnitude checks and led to a large miss in test requirements.

Highlighted the need for multiphase CO_2 validation data for not only the turbine design, but also the loop design

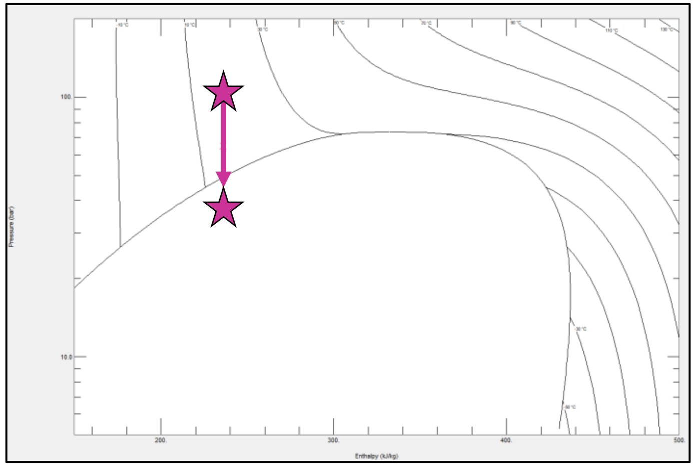


MULTIPHASE NOZZLE TESTING

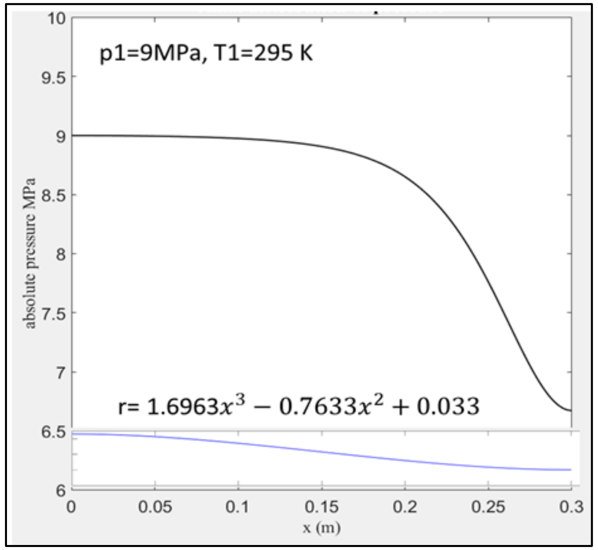
A converging-diverging nozzle design selected pressure loss and multiphase CFD validation data



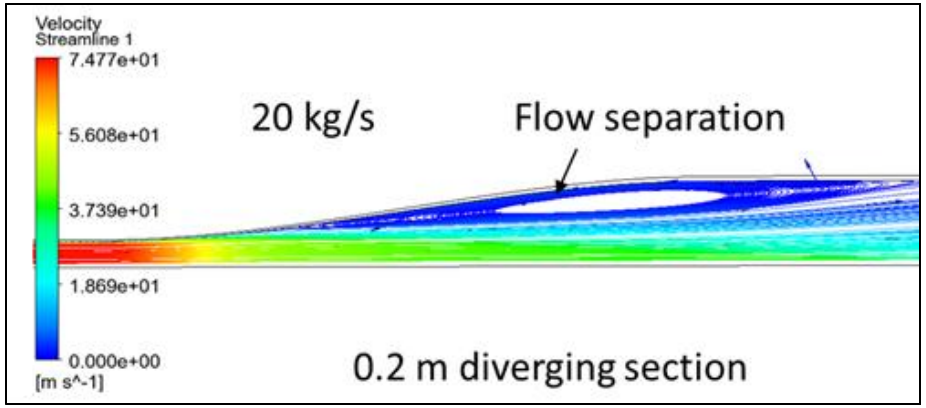
1. Liquid at inlet and expand to the highest vapor fraction possible



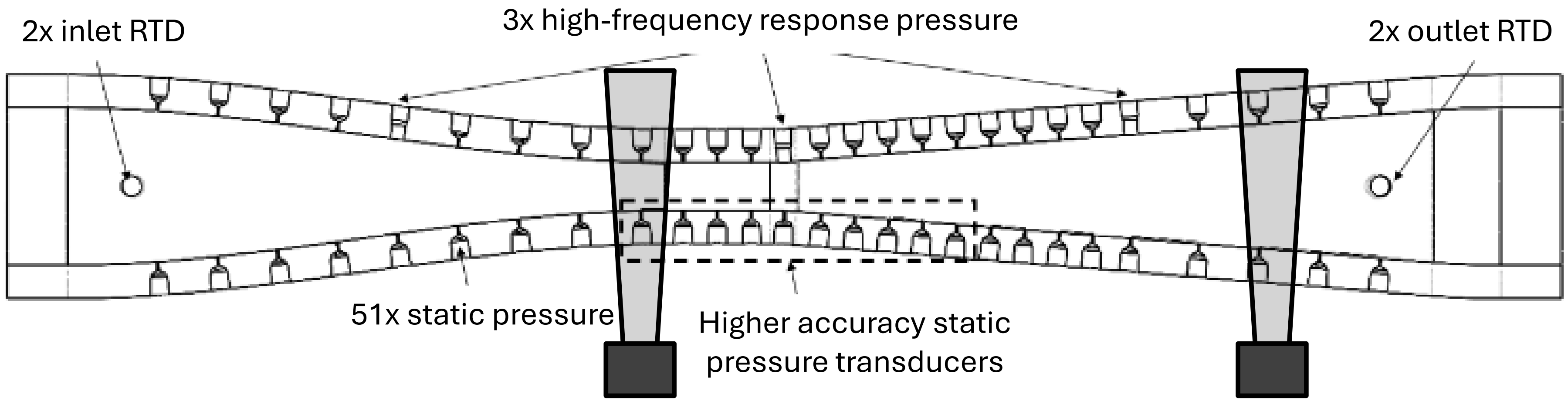
2. Inlet design to accommodate measurability and manufacturability



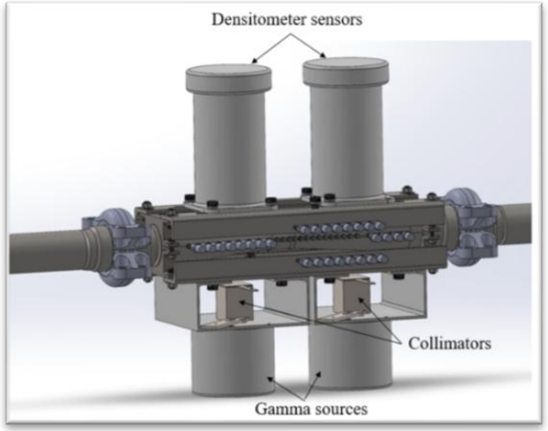
3. Throat was made as long as possible, and the diverging section was made linear and long enough to prevent flow separation

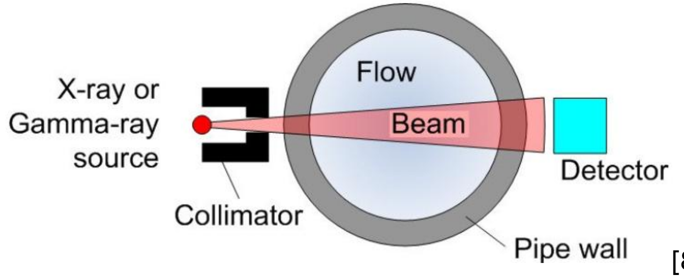


Detailed nozzle instrumentation included:



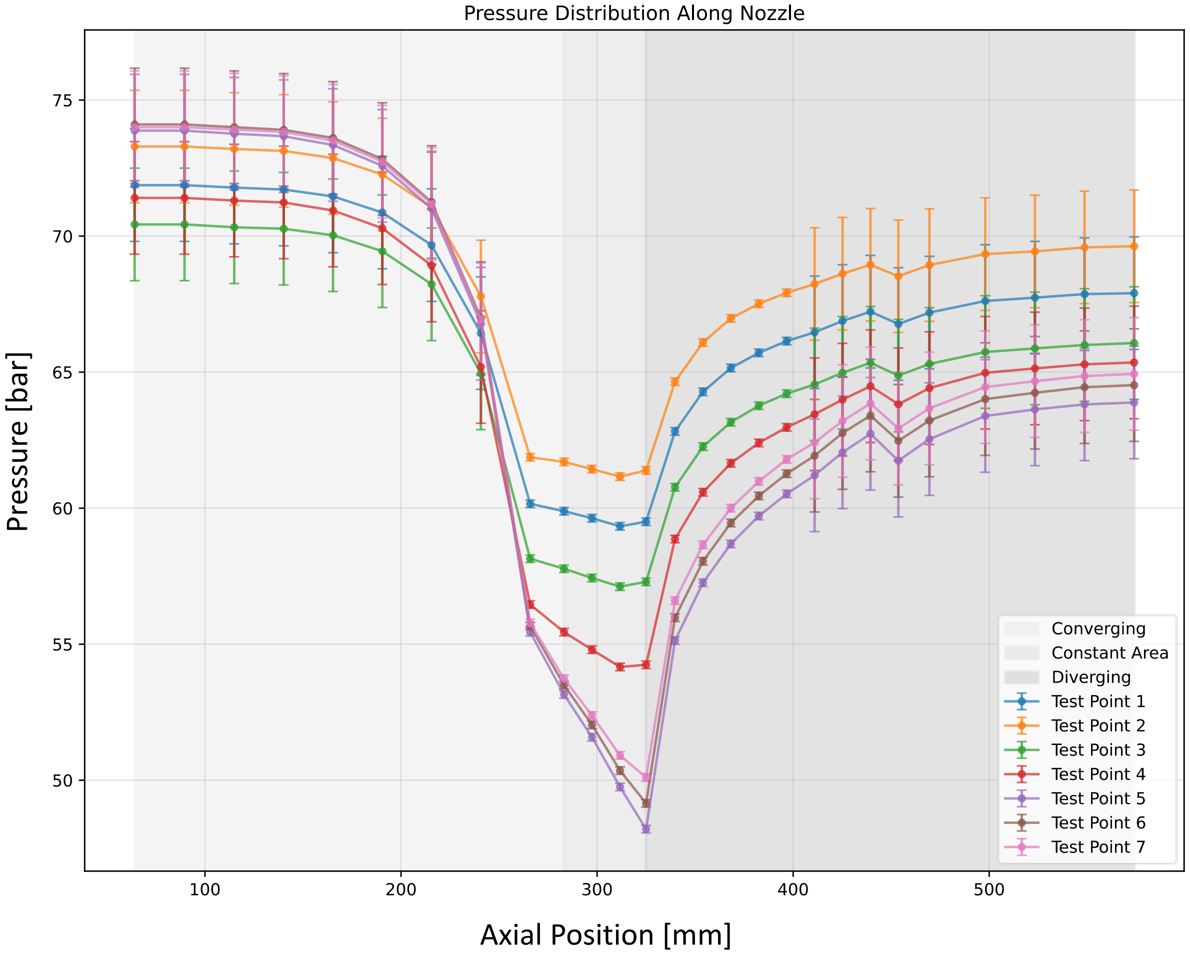
2x Gamma-ray densitometers



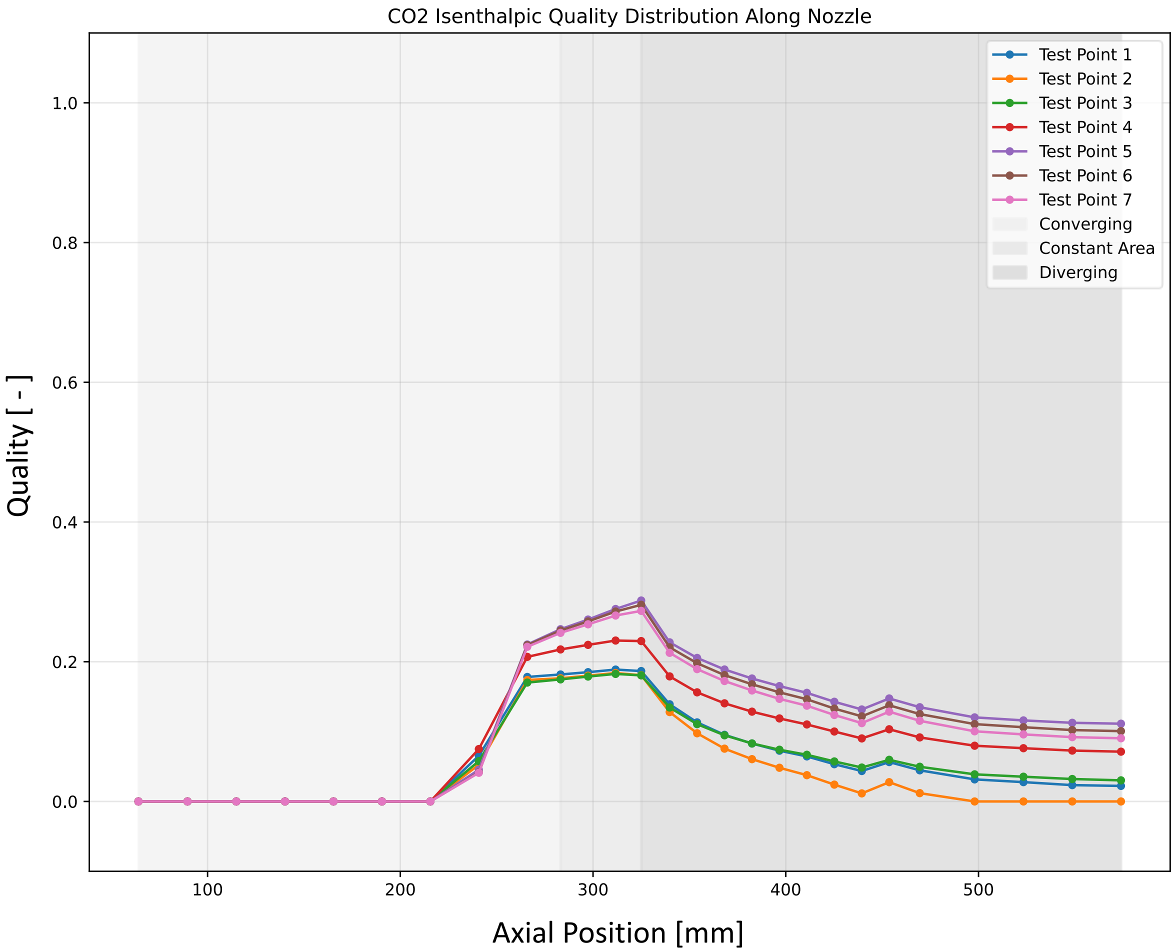


[8]

Multiphase flow was confirmed through an isenthalpic process assumption and densitometer data

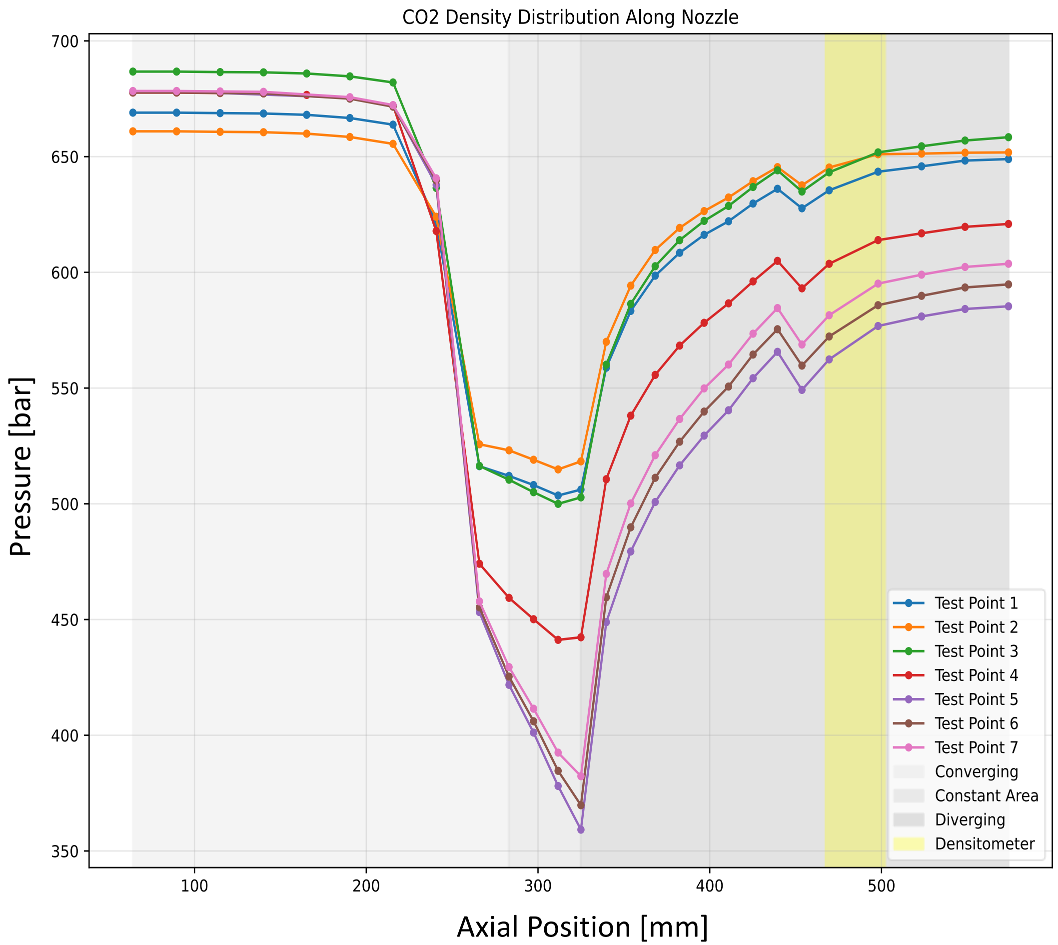


Pressure data showed pressure drops between 4.0-9.6 bar

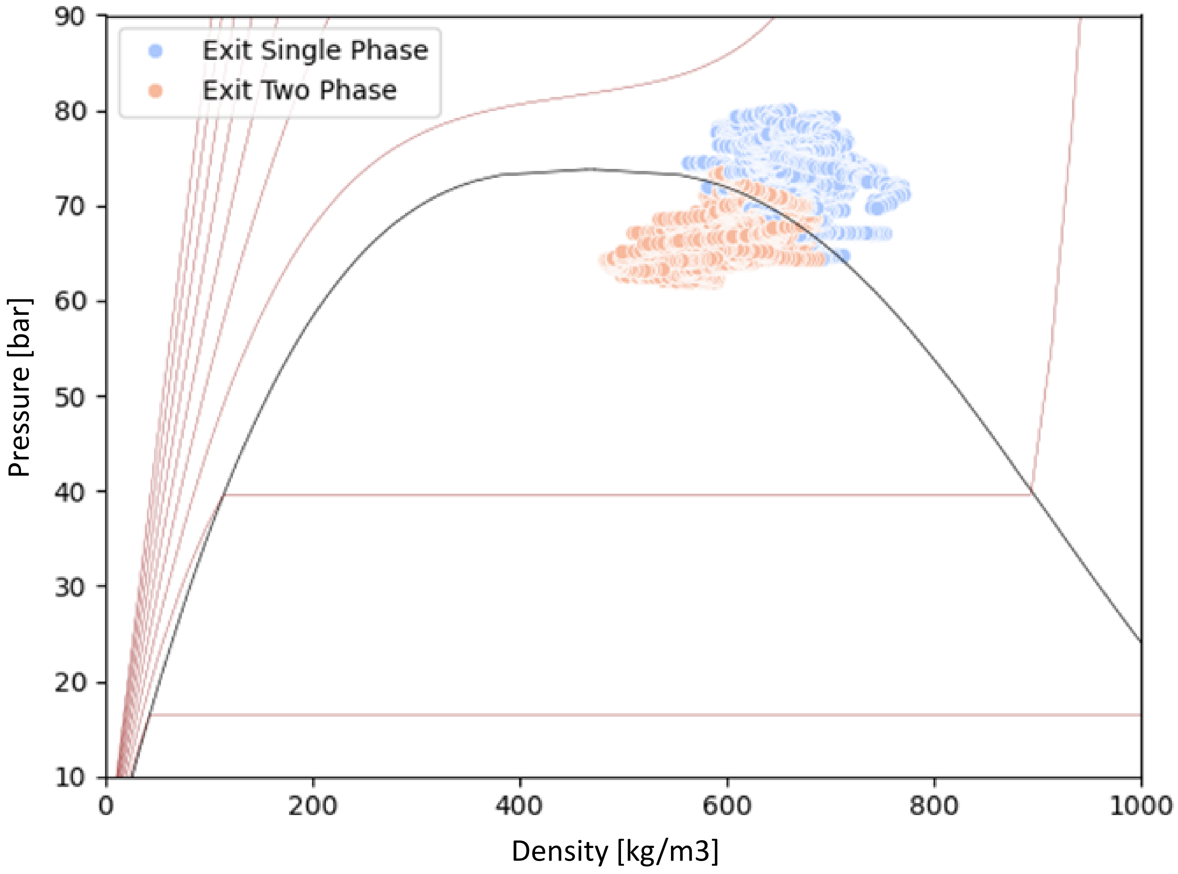


Quality estimated from isenthalpic process

Multiphase flow was confirmed through an isenthalpic process assumption and densitometer data

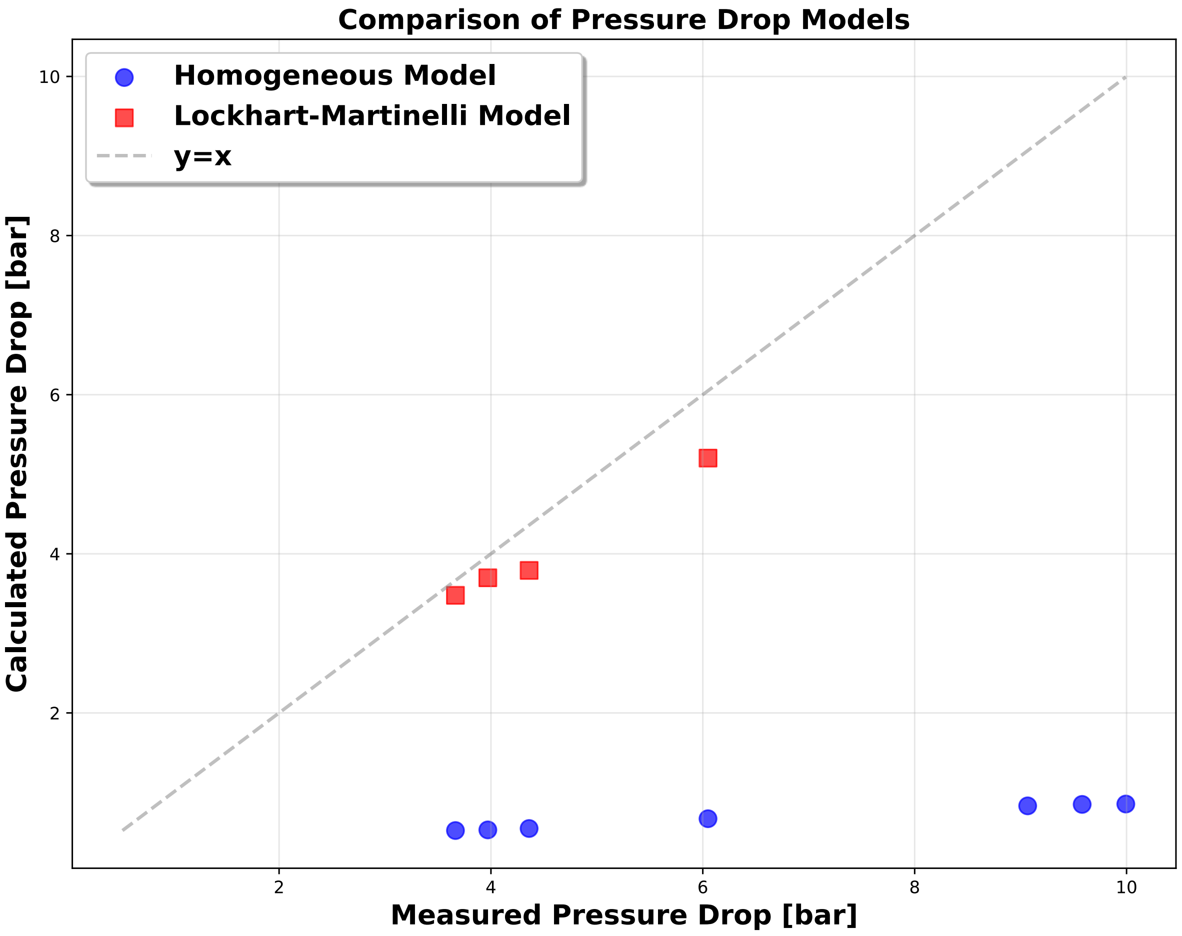


Density estimated from isenthalpic process



Density measurements from densitometer

The Lockhart-Martinelli multiphase pressure drop model is much more appropriate than homogenous Darcy-Weisbach



Homogenous Model: Darcy-Weisbach [9]

$$\Delta P_{total} = \int_0^L f(x) \frac{dx}{D(x)} \frac{\rho(x) v(x)^2}{2}$$

f = Darcy friction factor

L = pipe length

D = pipe diameter

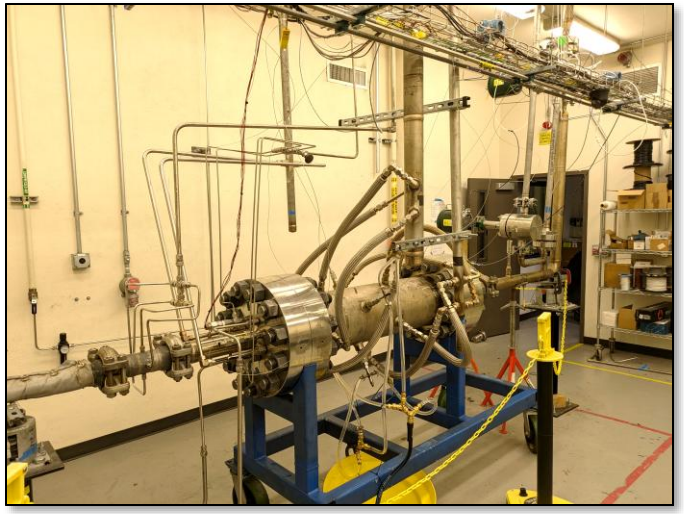
ρ = fluid mixture density

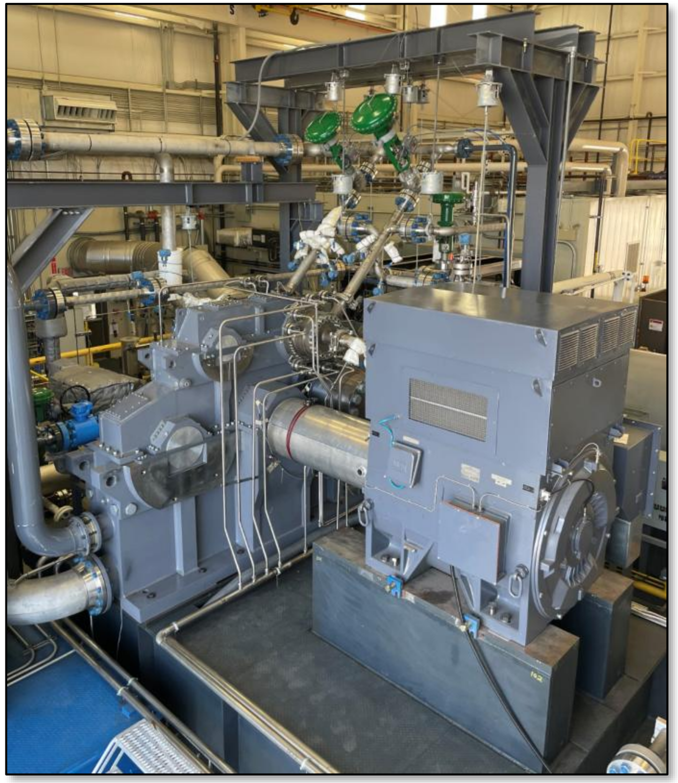
v = fluid mixture velocity

Lockhart-Martinelli Model [10]: Two-phase pressure drop multiplier

$$\phi_{lo}^2 = 1 + \frac{20}{X} + \frac{1}{X^2}$$

$$X = \sqrt{\left(\frac{f}{2D}\right) \cdot \frac{(1 - VMF)^2}{VMF^2} \cdot \left(\frac{\rho_v}{\rho_l}\right)}$$





STEP, Oxy-combustion, Compander with IGV

OTHER SCO2 TESTING ACCOMPLISHMENTS

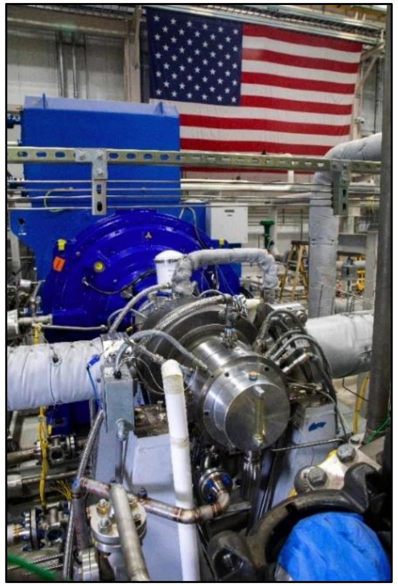
STEP sCO_2 Technology Maturation Achievements

- Successfully demonstrated gas-fired indirect sCO_2 plant operation at 500 °C simple recuperated cycle "max" conditions generating ~4 MW net power while grid-synchronized
- All major components commercially procured except turbine jointly designed by GE Vernova and SwRI:
  - Compressors: Baker Hughes
  - Heat Exchangers: Parker Heatric, Optimus, Vacuum Process Engineering
  - Heater Protection Valve and 500 °C Turbine Trip Valve: SchuF, AVS/HORA
  - Plant Controller: GE Mark VI
- Demonstrated repeatability through multiple operations, also safely demonstrated fast and slow trips
- Project Partners:

U.S. DEPARTMENT OF ENERGY · NATIONAL ENERGY TECHNOLOGY LABORATORY · GTI ENERGY · SwRI · GE VERNOVA

- Plant design details available to JIP members

KEPCO · Natural Resources Canada · Southern Company · Texas Commission on Environmental Quality · ENGIE · CSIRO · American Electric Power · EGAT



Thank you

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GT2025-154034
The Design of a Multiphase CO2 Turbine Test Facility

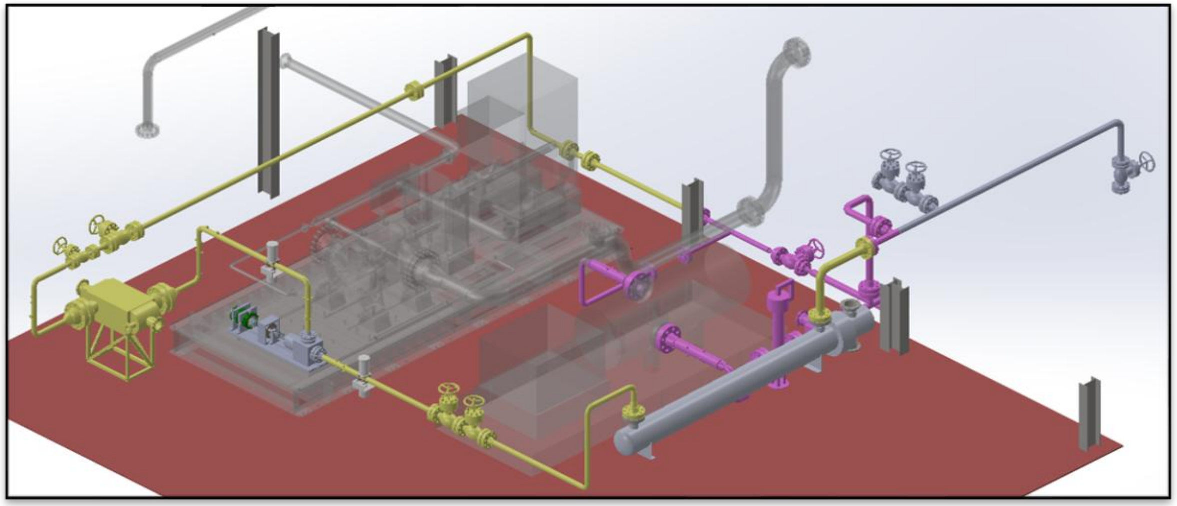
GT2025-154157
Experimental Investigation of Vapor Formation in Liquid CO2 Flow Through a Converging-Diverging Nozzle

U.S. DEPARTMENT OF ENERGY

SwRI

ECHOGEN power systems

FLOWSERVE



References

1. McTigue, Farres-Antunez, Ellingwood, Neises, White, 2020, “Pumped thermal electricity storage with supercritical CO2 cycles and solar heat input,” *AIP Conference Proceedings* 2303, 190024.
2. Aga, V., Conte, E., Carroni, R., Burcker, B., & Ramond, M. (2016, March). Supercritical CO2-based heat pump cycle for electrical energy storage for utility scale dispatchable renewable energy power plants. *In Proc: 5th Int. Symp.—Supercritical CO2 Power Cycles* (San Antonio, United States).
3. Wikipedia, “Two-Phase Flow,” https://en.m.wikipedia.org/wiki/Two-phase_flow
4. Supak, Kevin, et al. "Two-Phase CO2 Flow Behavior in Horizontal Piping." *International Pipeline Conference*. Vol. 88582. American Society of Mechanical Engineers, 2024.
5. Lettieri, Claudio, et al. "Characterization of nonequilibrium condensation of supercritical carbon dioxide in a de laval nozzle." *Journal of Engineering for Gas Turbines and Power* 140.4 (2018): 041701.
6. Kaupert, Kevin, et al. "Flashing liquid expanders for LNG liquefaction trains." *Proceedings of 17th International Conference & Exhibition on Liquefied Natural Gas (LNG 17)*. Gas Technology Institute (GTI), Houston, USA. (2013).
7. Hosangadi, Ashvin, et al. "Numerical Predictions of Mean Performance and Dynamic Behavior of a 10 MWe SCO2 Compressor With Test Data Validation." *Journal of Engineering for Gas Turbines and Power* 144.12 (2022): 121019.
8. https://nfogm.no/wp-content/uploads/2019/02/2009-05-X-ray-based-densitometer-for-multiphase-flow-measurement-Tjugum-Roxar.pdf
9. Moody, L. F., “Friction Factors for Pipe Flow,” Transactions of the ASME, 66, 8, November 1944, pp. 671-684.
10. Lockhart, R. W.; Martinelli, R. C. (1949). "Proposed correlation of data for isothermal two-phase, two-component flow in pipes". *Chemical Engineering Progress*. 45: 39–48