Benchmarking a Cryogenic Code to the FREIA Helium Liquefier

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The FREIA He Liquefier

Background and project motivation

- Helium liquefier from Linde group
- Liquid He - crucial for research infrastructure
- Simulations of thermodynamics – better understanding of liquefaction process
- Main objective: build a theoretical model of the FREIA liquefier based upon the principle of enthalpy conservation

Linde liquid He production and recovery system – linde-engineering.com

Thermodynamics Background

- Intensive quantities: T, P
- Extensive quantities: U, H, S, V
- Enthalpy

$$H = U + PV$$

- Equation of state for ideal gas

$$PV = nRT$$

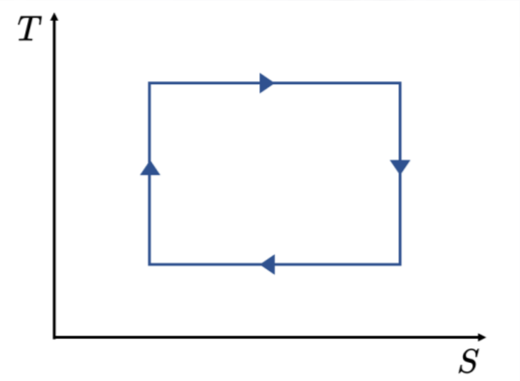
- Ideal gas vs real gas
- More complex relations for real gases – use CoolProp library

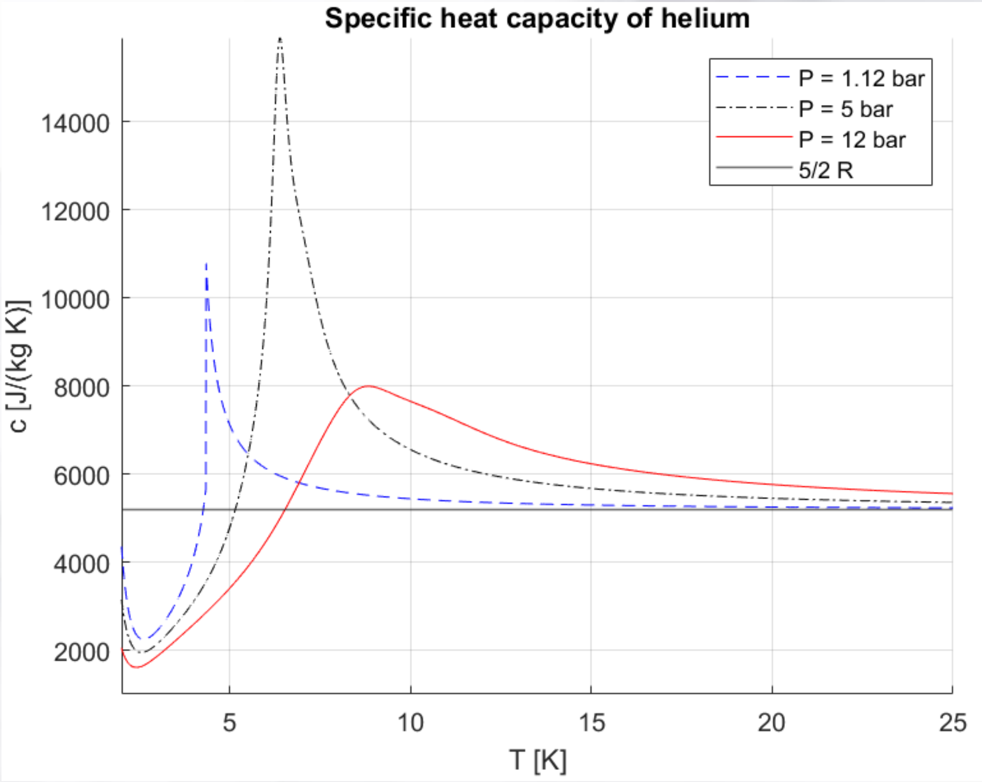
Thermodynamics Background

- Heat capacity $C = \frac{\partial Q}{\partial T}$
- Ideal monatomic gas: $c_V = \frac{3}{2}R$, $c_P = \frac{5}{2}R$
- Entropy - real and ideal processes

$$S \geq \frac{Q}{T}$$

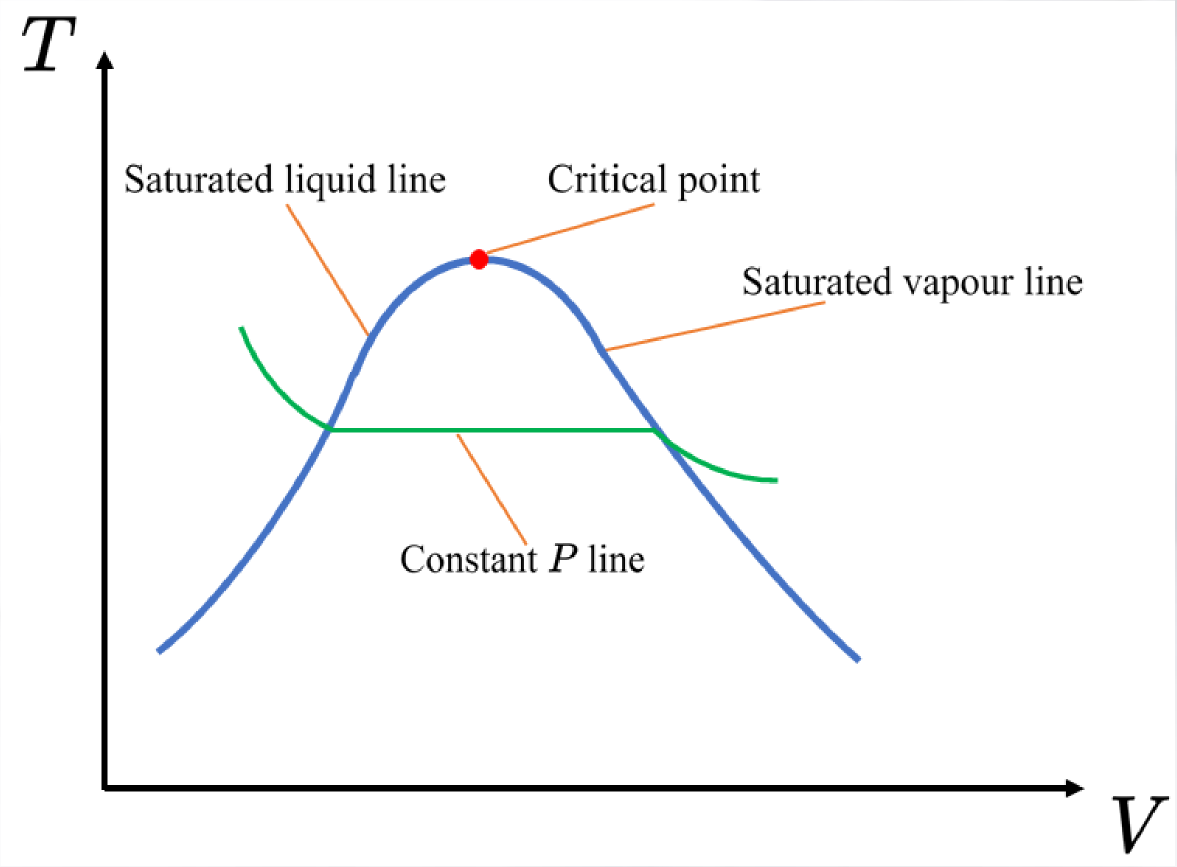
- Carnot heat cycle





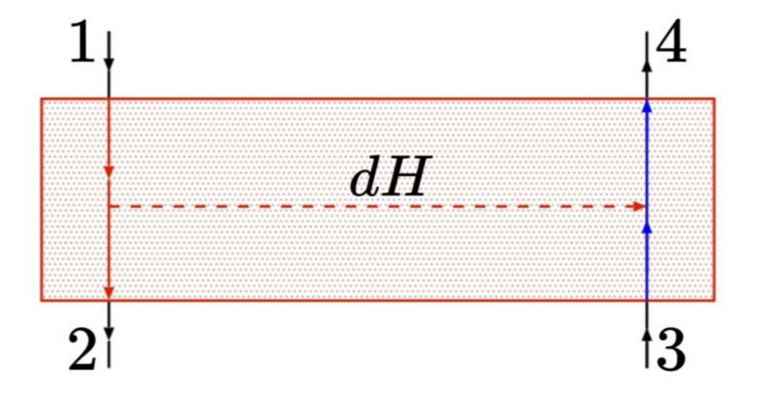
Thermodynamics Background

- Enthalpy and phases: latent heat
- Critical point
- Saturation dome
- Vapour quality
  - Saturated vapour: 100%
  - Saturated liquid: 0%



Cycle components: heat exchanger

- Parallel flows or counter-flow
- Enthalpy in heat exchanger



$$H_2 = H_1 - dH$$
$$H_4 = H_3 + dH$$

Cycle components: two-fluid counterflow heat exchanger

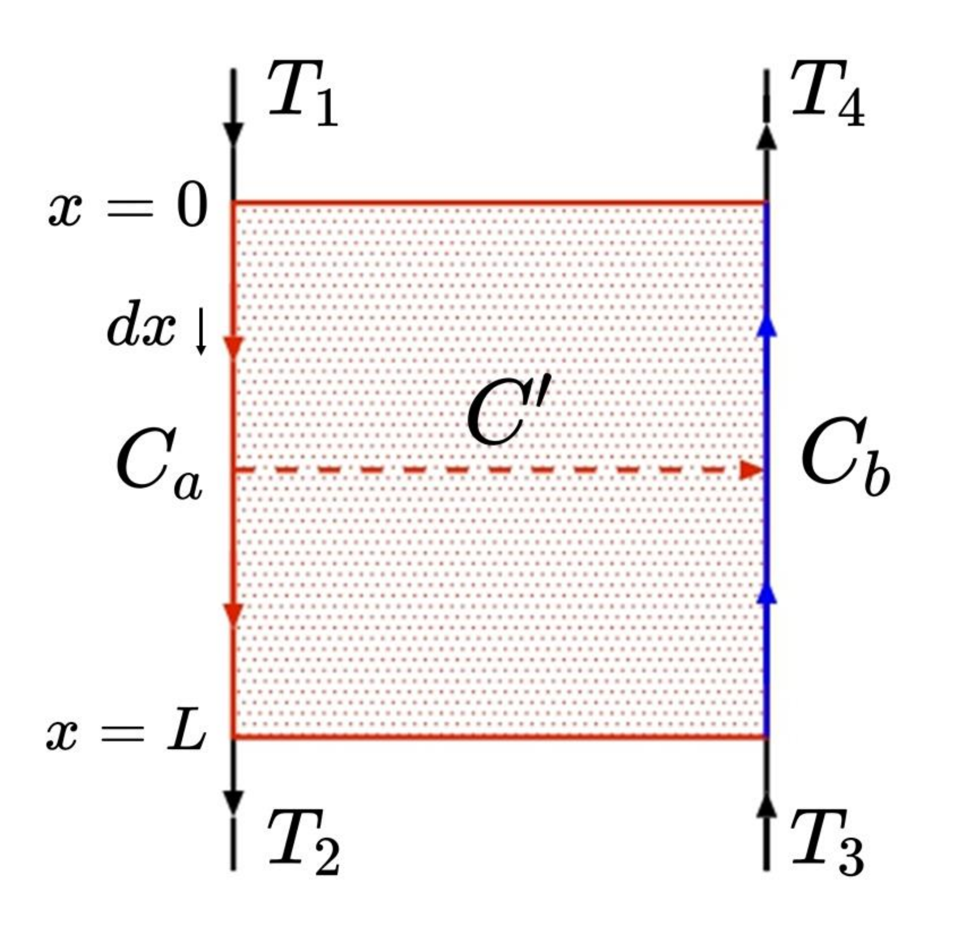
- Temperatures - system of 1st-order linear differental equations

$$\frac{d}{dx}\begin{bmatrix} T_a \\ T_b \end{bmatrix} = \begin{bmatrix} -\frac{C'}{C_a} & \frac{C'}{C_a} \\ -\frac{C'}{C_b} & \frac{C'}{C_b} \end{bmatrix} \begin{bmatrix} T_a \\ T_b \end{bmatrix}$$

  - Linear solution

$$\begin{bmatrix} T_a \\ T_b \end{bmatrix} = A_1 \vec{v}_1 e^{\alpha_1 x} + A_2 \vec{v}_2 e^{\alpha_2 x}$$

where A_1, A_2 come from boundary conditions, α_i is the eigenvalue and $\vec{v}_i$ is the eigenvector



Cycle components: two-fluid counterflow heat exchanger

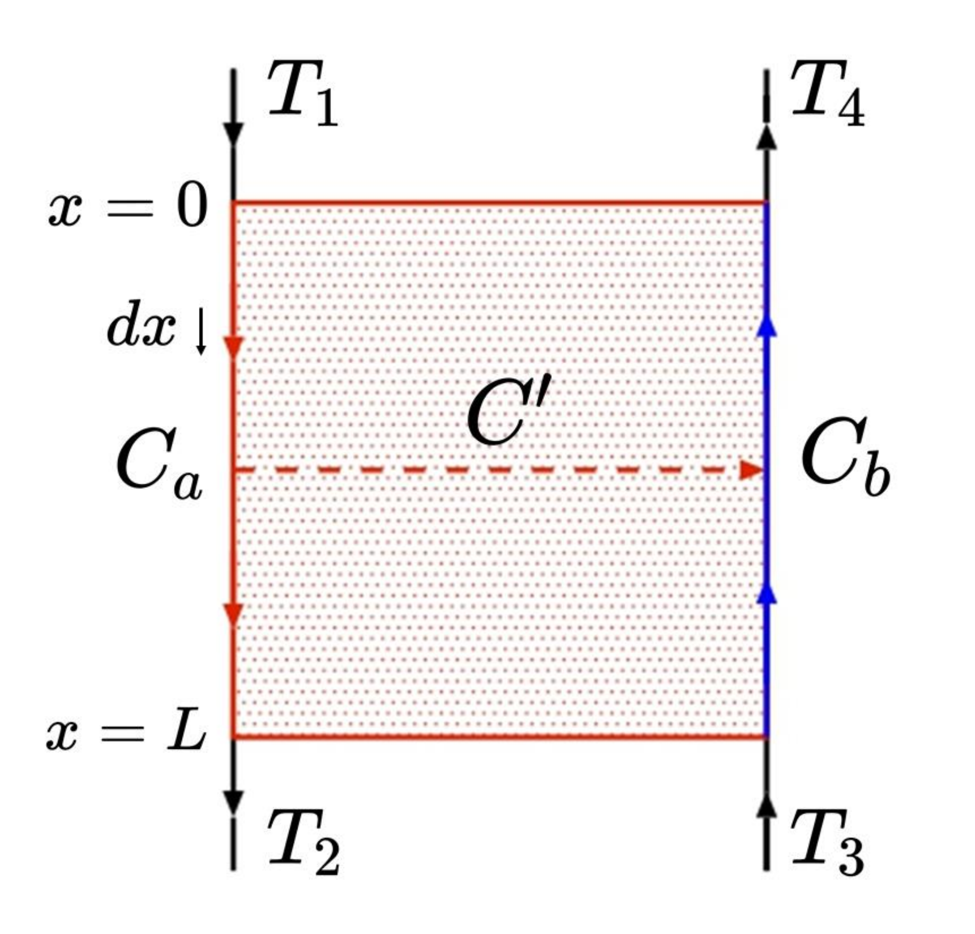
- Solve for total enthalpy transfer $\Delta\dot{H}$

$$\Delta\dot{H} = C_H(T_3 - T_1)$$

  - If $(C_a \neq C_b)$: $C_H = \frac{C_a C_b (1-e^{-\alpha})}{C_a e^{-\alpha} - C_b}$
  - If $(C_a = C_b)$: $\frac{1}{C_H} = \frac{1}{C_a} + \frac{1}{C'L}$

where $\alpha = C'\left(\frac{1}{C_a} - \frac{1}{C_b}\right)$

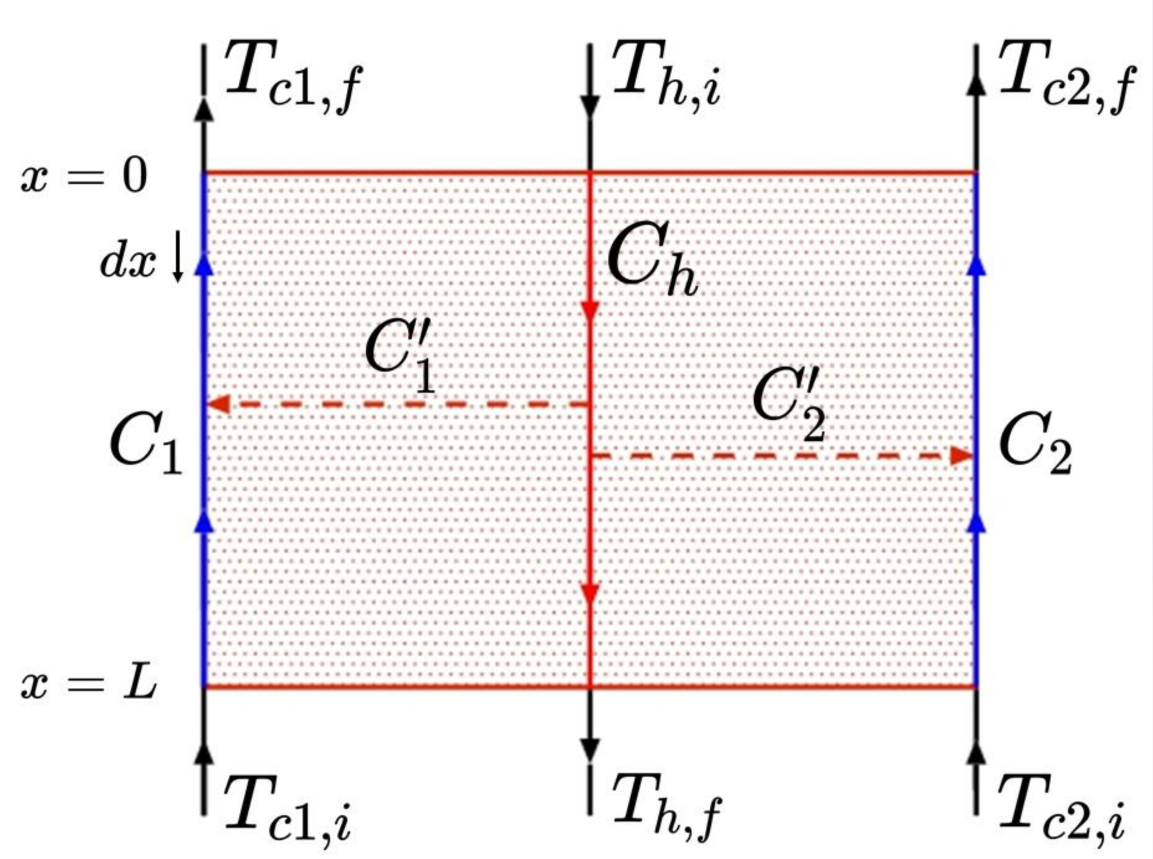
  - Solved for analytically



Cycle components: three-fluid counterflow heat exchanger

- Same principle with heat equations

$$\frac{d}{dx}\begin{bmatrix} T_{c1} \\ T_h \\ T_{c2} \end{bmatrix} = \begin{bmatrix} \frac{C_1'}{C_1} & -\frac{C_1'}{C_1} & 0 \\ \frac{C_1'}{C_h} & -\frac{(C_1'+C_2')}{C_h} & \frac{C_2'}{C_h} \\ 0 & -\frac{C_2'}{C_2} & \frac{C_2'}{C_2} \end{bmatrix} \begin{bmatrix} T_{c1} \\ T_h \\ T_{c2} \end{bmatrix}$$



- Solution:

$$\begin{bmatrix} T_{c1} \\ T_h \\ T_{c2} \end{bmatrix} = A_1 \vec{v}_1 e^{\alpha_1 x} + A_2 \vec{v}_2 e^{\alpha_2 x} + A_3 \vec{v}_3 e^{\alpha_3 x}$$

Cycle components: three-fluid counterflow heat exchanger

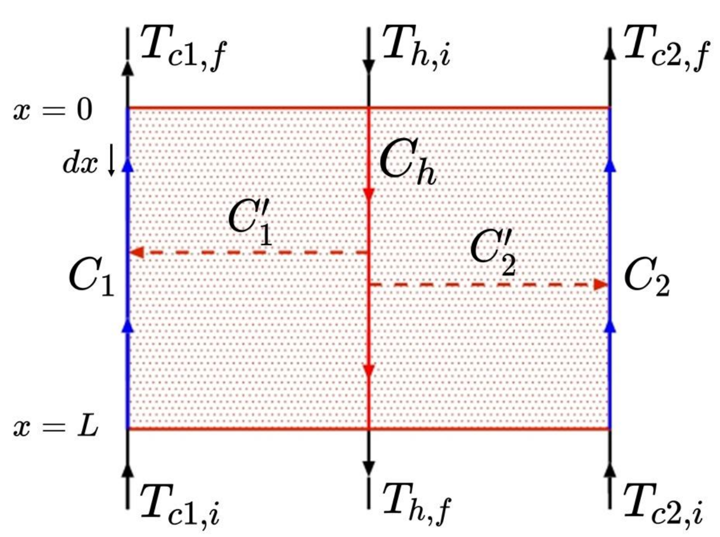
- Solving for total enthalpy transfer $\Delta\dot{H}_1, \Delta\dot{H}_2$

$$\Delta\dot{H}_1 = C_1'\left(\frac{A_1(v_{21}-v_{11})(e^{\alpha_1 L}-1)}{\alpha_1} + \frac{A_2(v_{22}-v_{12})(e^{\alpha_2 L}-1)}{\alpha_2} + \frac{A_3(v_{23}-v_{13})(e^{\alpha_3 L}-1)}{\alpha_3}\right)$$

$$\Delta\dot{H}_2 = C_2'\left(\frac{A_1(v_{21}-v_{31})(e^{\alpha_1 L}-1)}{\alpha_1} + \frac{A_2(v_{22}-v_{32})(e^{\alpha_2 L}-1)}{\alpha_2} + \frac{A_3(v_{23}-v_{33})(e^{\alpha_3 L}-1)}{\alpha_3}\right)$$

where α_i is the eigenvalue and $\vec{v}_i = \begin{bmatrix} v_{1i} \\ v_{2i} \\ v_{3i} \end{bmatrix}$ is the corresponding eigenvector

- Long analytic expressions with respect to two-fluid case, but still easy numerically
- In FREIA liquefier: two versions, one with cold flow 2 reversed

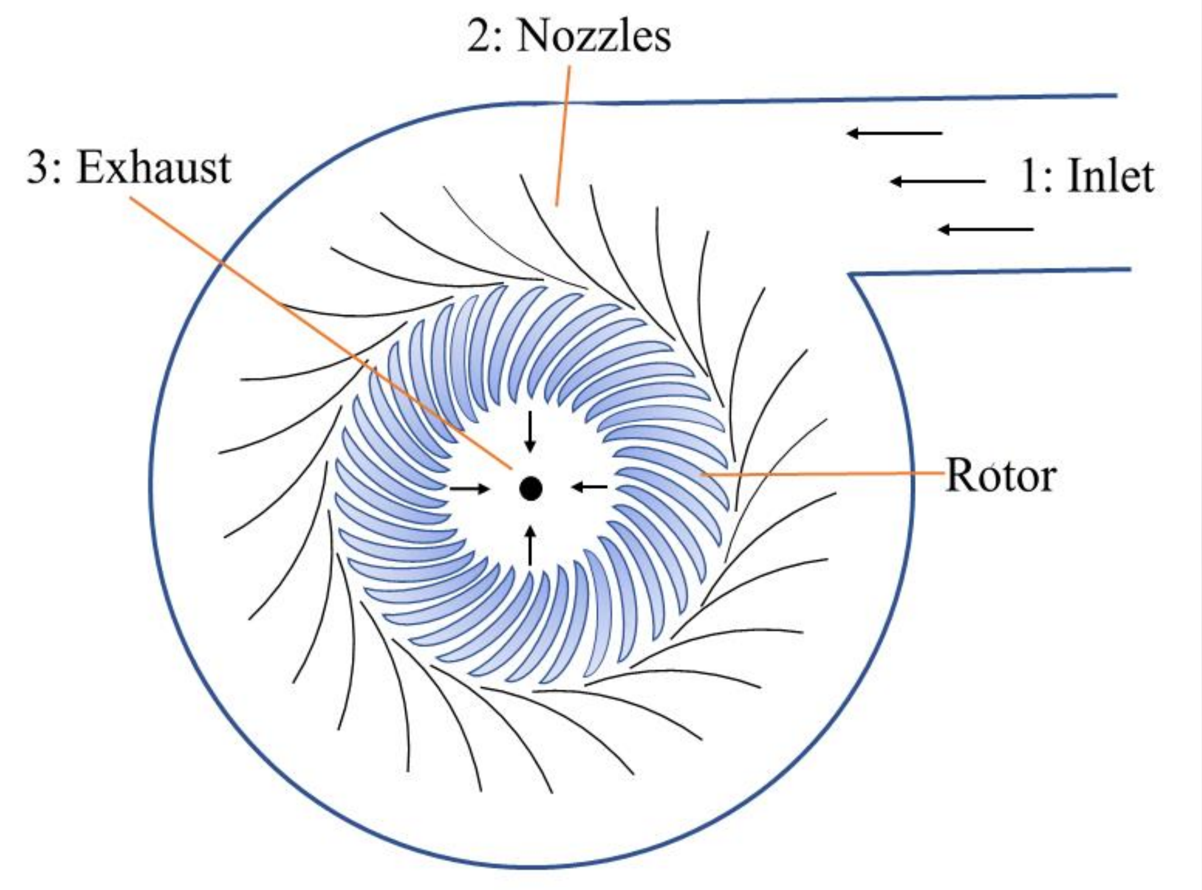


Cycle components: turboexpander

- Work against centrifugal force
- Ideal gas at sonic speeds and isentropic expansion

$$\frac{T_1}{T_3} = 2 \qquad \frac{P_1}{P_3} = 5.64$$

- Gas must not liquefy



Drawing of a turboexpander

Cycle component: Joule-Thomson valve

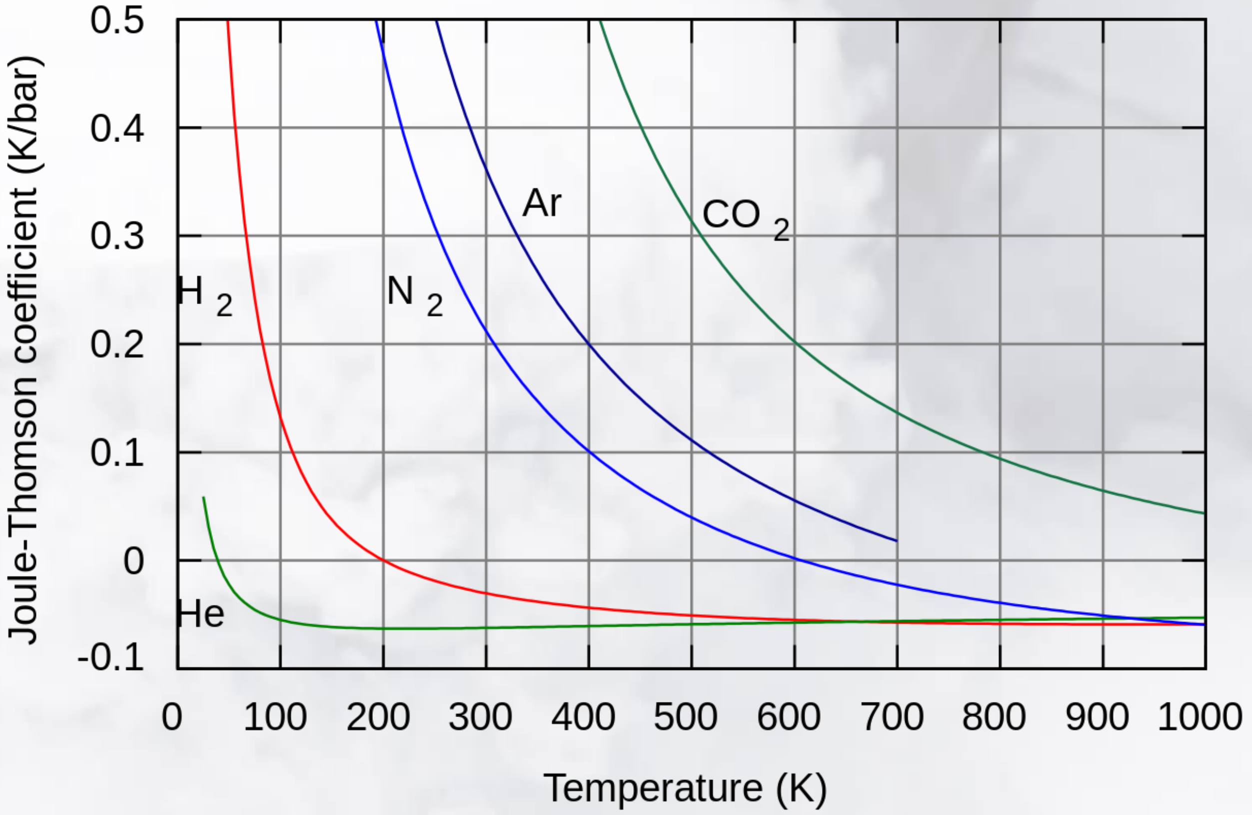
- Joule-Thomson (JT) Effect
  - Temperature change of real gas
  - Irreversible, isenthalpic process:

$$\Delta H = 0$$

  - JT coefficient

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_{H=\mathrm{const}}$$

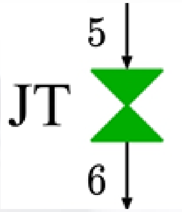
  - Inversion temperature



JT Coefficient at 1 bar. Image courtesy: Hankwang, Wikimedia Commons

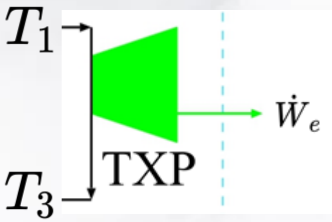
Cycle components – MATLAB implementation

- JT valve




```
%JT-valve - isenthalpic process
h5 = py.CoolProp.CoolProp.PropsSI('H','P',P5,'T',T5,'Helium');
h6 = h5;
T6 = py.CoolProp.CoolProp.PropsSI('T','P',P6,'H',h6,'Helium');
```

- Turboexpander




```
%Turboexpander for helium
h1 = py.CoolProp.CoolProp.PropsSI('H','P',P1,'T',T1,'Helium');
T3 = T1/2;
P3 = P1/5.64;
h3 = py.CoolProp.CoolProp.PropsSI('H','P',P3,'T',T3,'Helium');
deltah = h1 - h3;
We = m*deltah;
```

Liquefaction cycles – Linde-Hampson

- Most fundamental cycle, 1895
- 1^{st} law of thermodynamics in dashed control volume

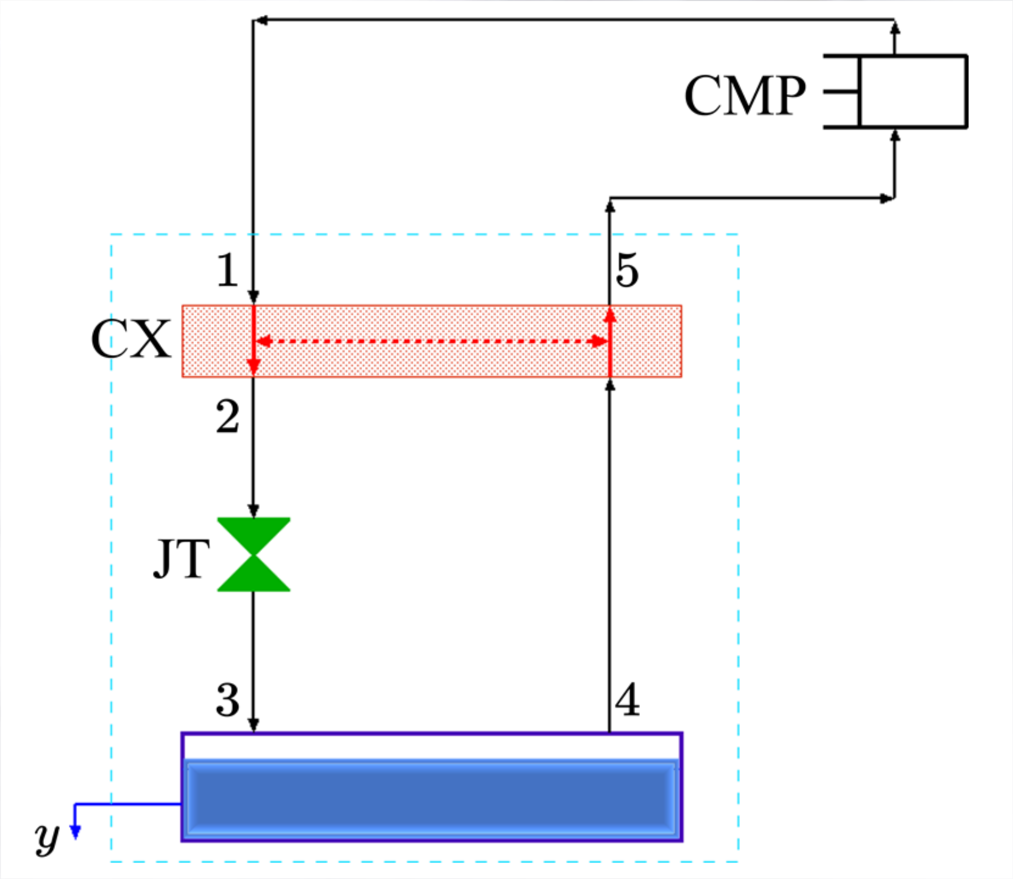
$$\dot{m}h_1 = \dot{m}_f h_f + (\dot{m} - \dot{m}_f)h_5$$

Global yield: $$y \equiv \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_5}{h_f - h_5}$$

Around phase separator:

$$\dot{m}h_2 = \dot{m}_f h_f + (\dot{m} - \dot{m}_f)h_4$$

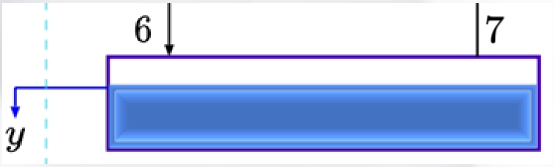
Local yield: $$y_l \equiv \frac{\dot{m}_f}{\dot{m}_3} = \frac{h_2 - h_4}{h_f - h_4}$$



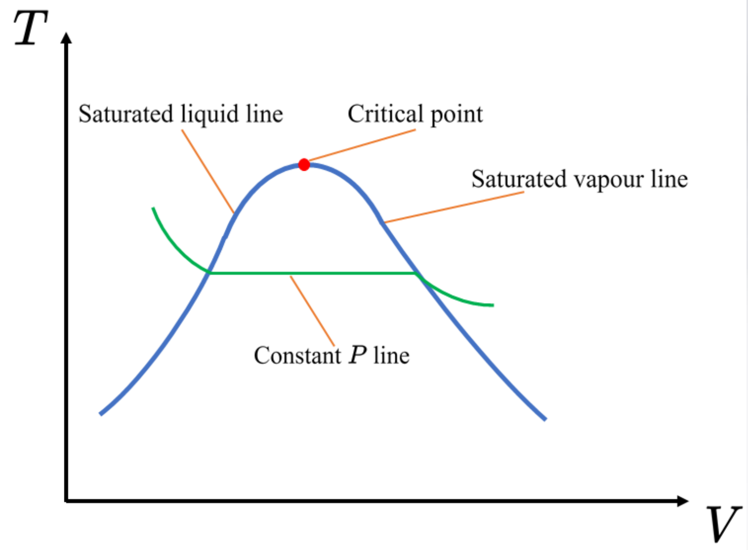
Liquefaction – MATLAB implementation

- Phase separator

```
if T6 < 5.1953  %critical point of He
% enters liquid phase
hliq= py.CoolProp.CoolProp.PropsSI('H','T',T6,'Q',0,'Helium'); %specific heat capacity
hgas= py.CoolProp.CoolProp.PropsSI('H','T',T6,'Q',1,'Helium');
y1=(hgas-H5/Q5)/(hgas-hliq); y1=min(1,max(0,y1)); % local without HE
Hgas = H6 - y1*Q6*hliq;
H7= Hgas;
```



- No matter the cycle complexity, local yield is always the same!



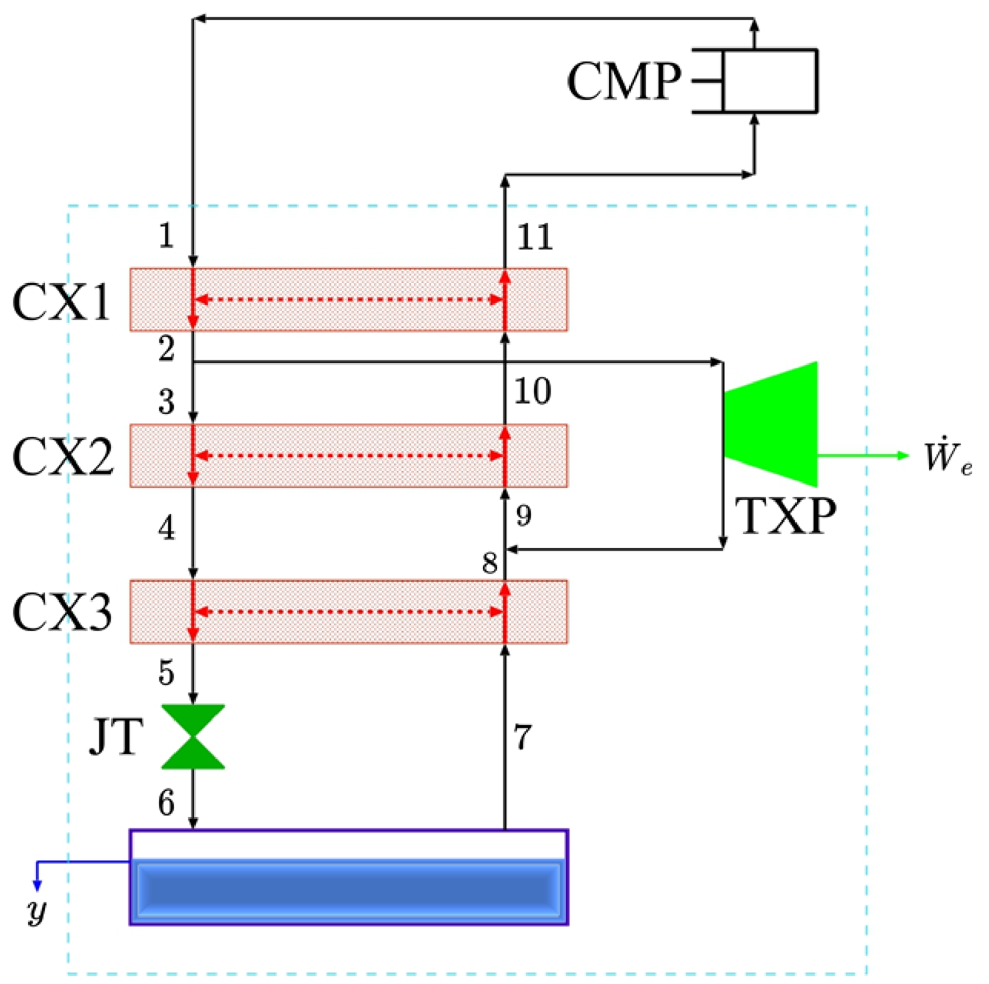
Liquefaction cycles - Claude

- Improvement, 1902
- Two more heat exchangers, isentropic expansion in turboexpander
- 1st law of thermodynamics

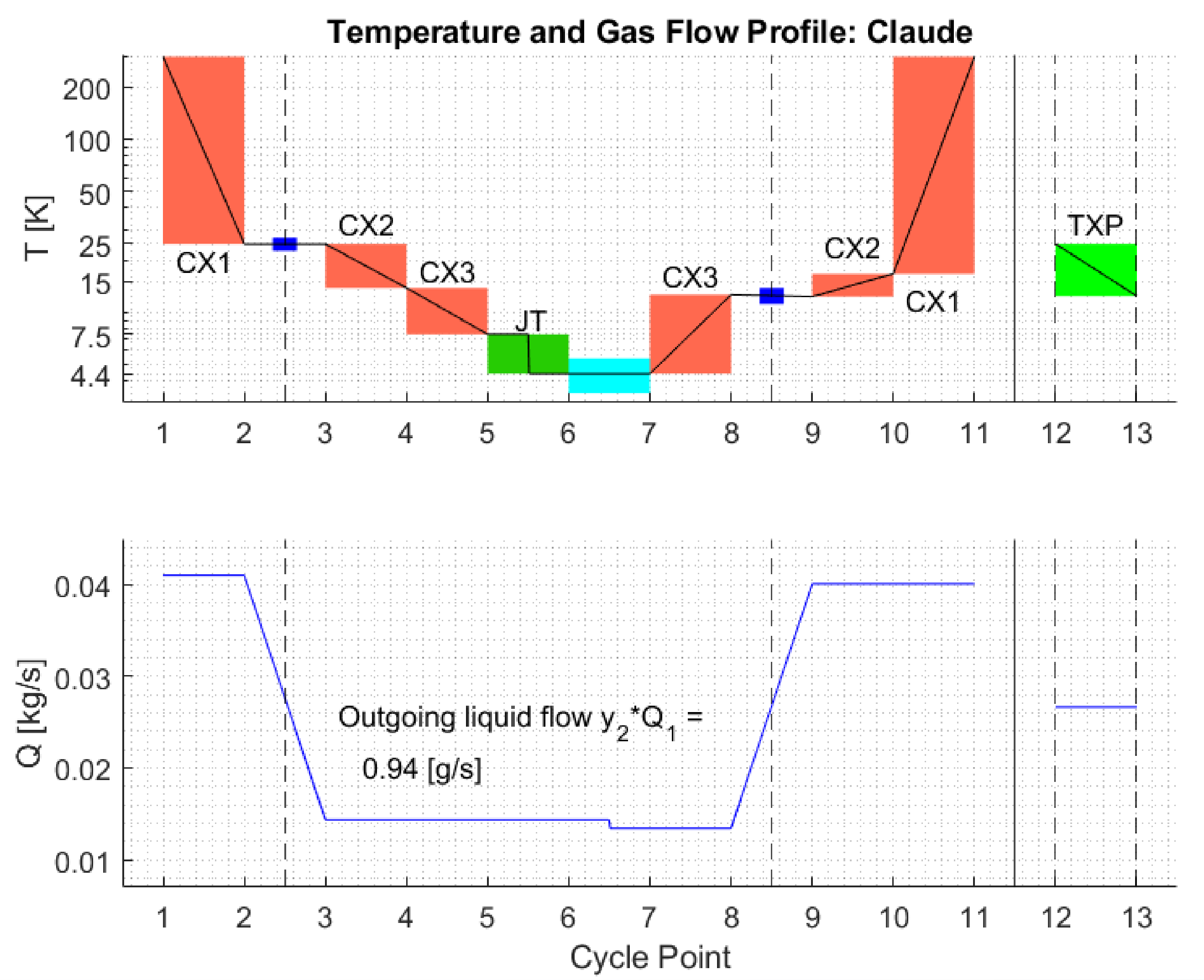
$$\dot{m}h_1 = \dot{W}_e + (\dot{m} - \dot{m}_f)h_{11} + \dot{m}_f h_f$$

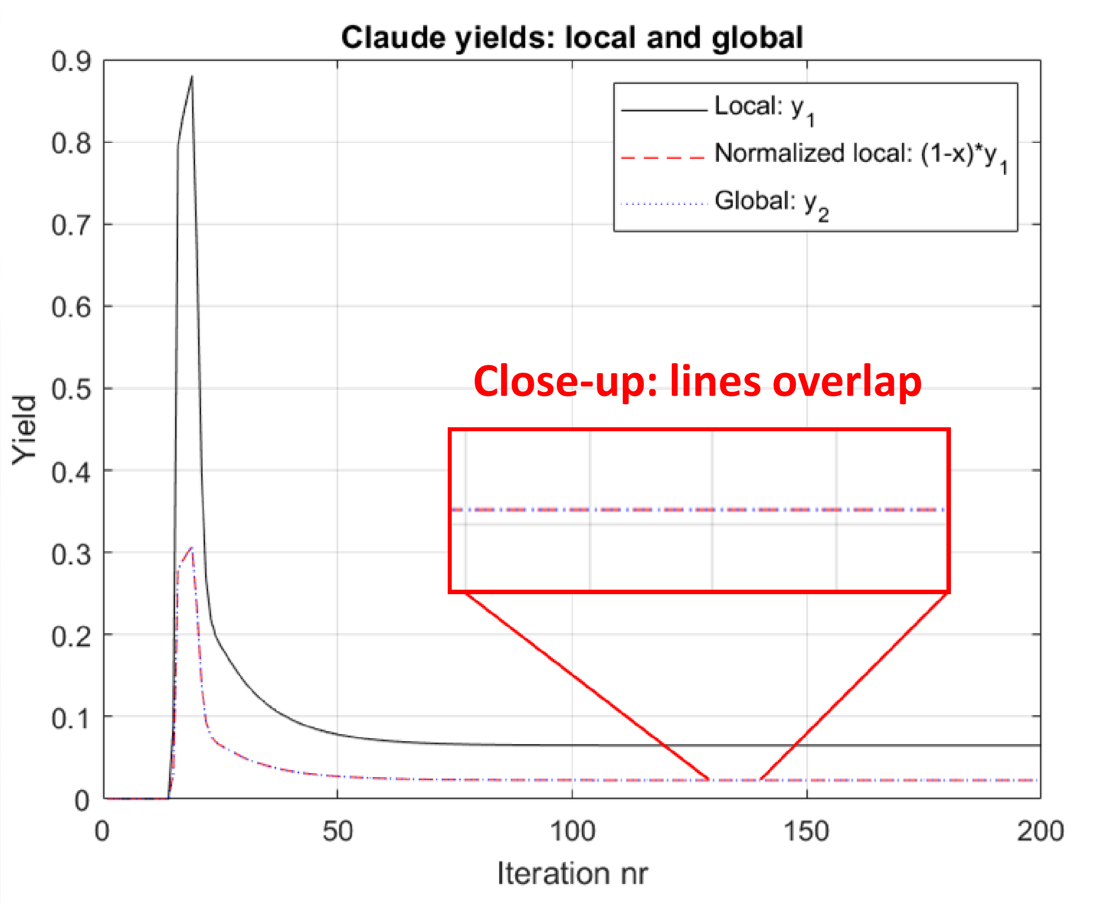
$$\dot{W}_e = \dot{m}_e h_2 - \dot{m}_e h_e \qquad x = \frac{\dot{m}_e}{\dot{m}}$$

$$y \equiv \frac{\dot{m}_f}{\dot{m}} = \frac{h_{11} - h_1}{h_{11} - h_f} + x\frac{h_2 - h_e}{h_{11} - h_f}$$



Claude cycle simulations





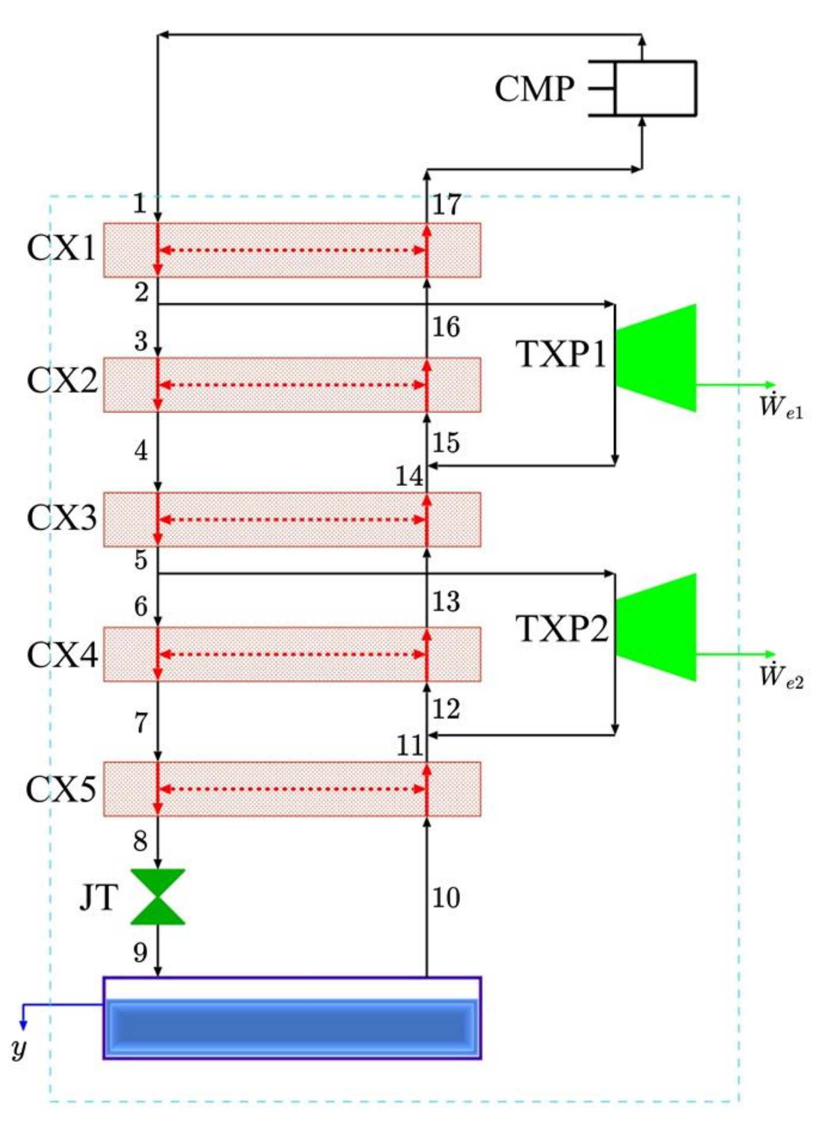
Liquefaction cycles - Collins

- Collins 1946
- Similar to Claude, but two more heat exchangers and one more turboexpander
- Analogously: 1st law around control volume gives

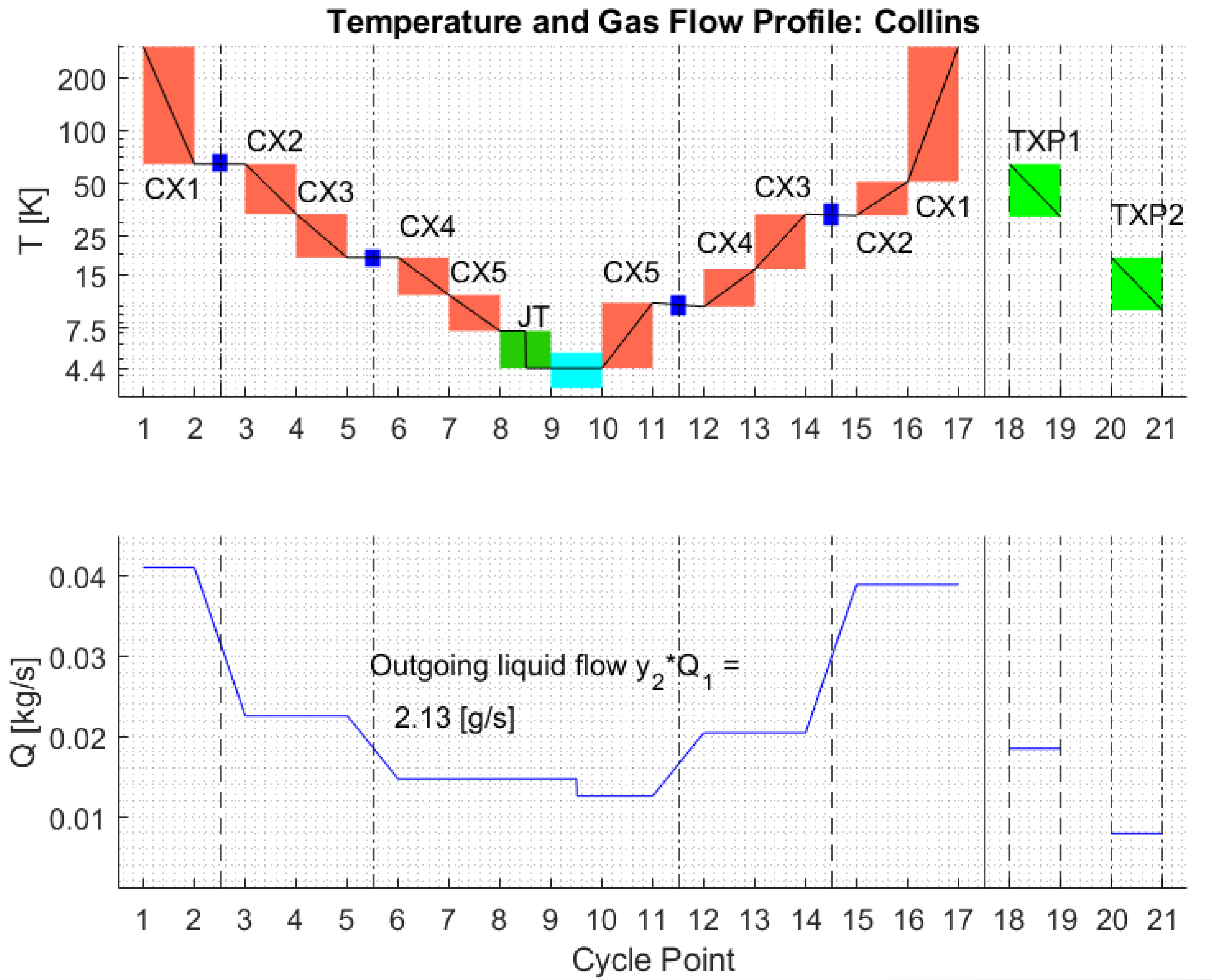
$$y \equiv \frac{\dot{m}_f}{\dot{m}} = \frac{h_{17} - h_1}{h_{17} - h_f} + x_1 \frac{\Delta h_{e1}}{h_{17} - h_f} + x_2 \frac{\Delta h_{e2}}{h_{17} - h_f}$$

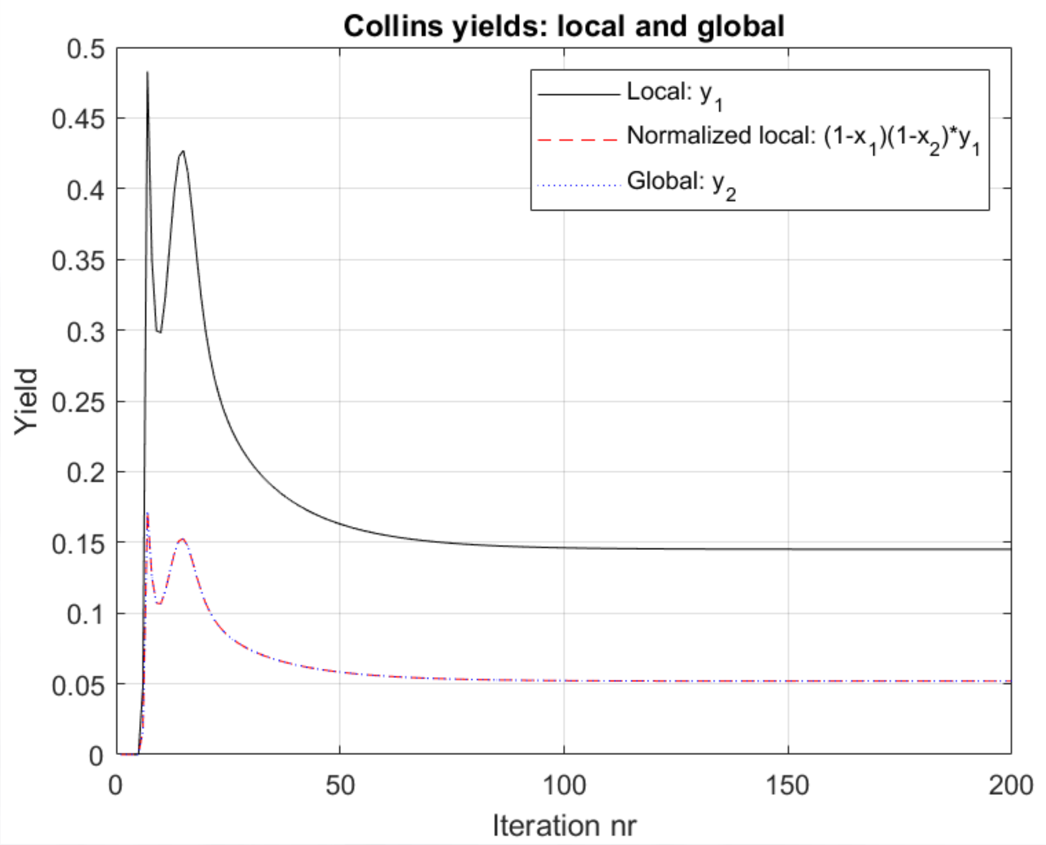
with

$$\dot{W}_{e_i} = \dot{m}_{e_i} \Delta h_{e_i} \qquad x_i = \frac{\dot{m}_{e_i}}{\dot{m}}, \qquad i = 1, 2$$

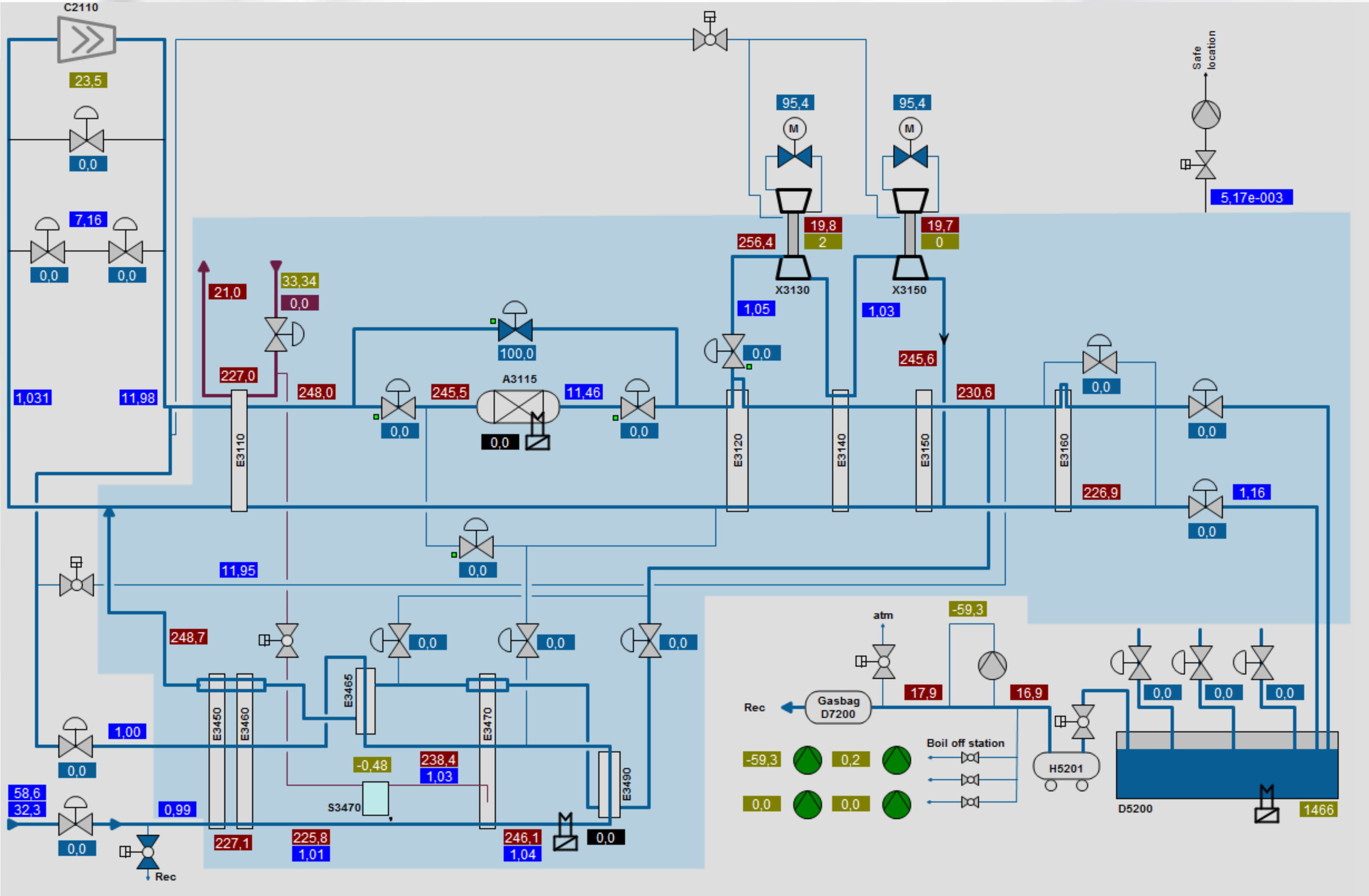


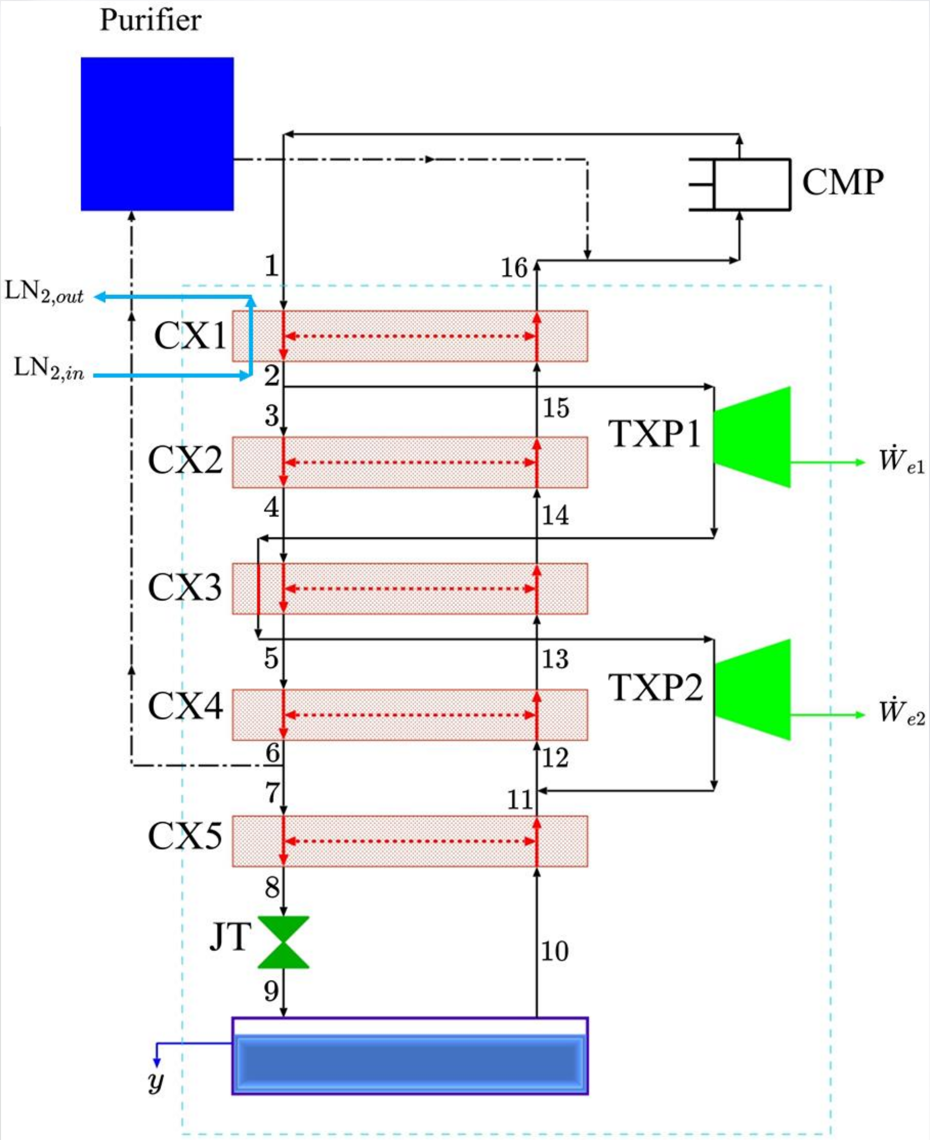
Collins cycle simulations





The FREIA liquefier





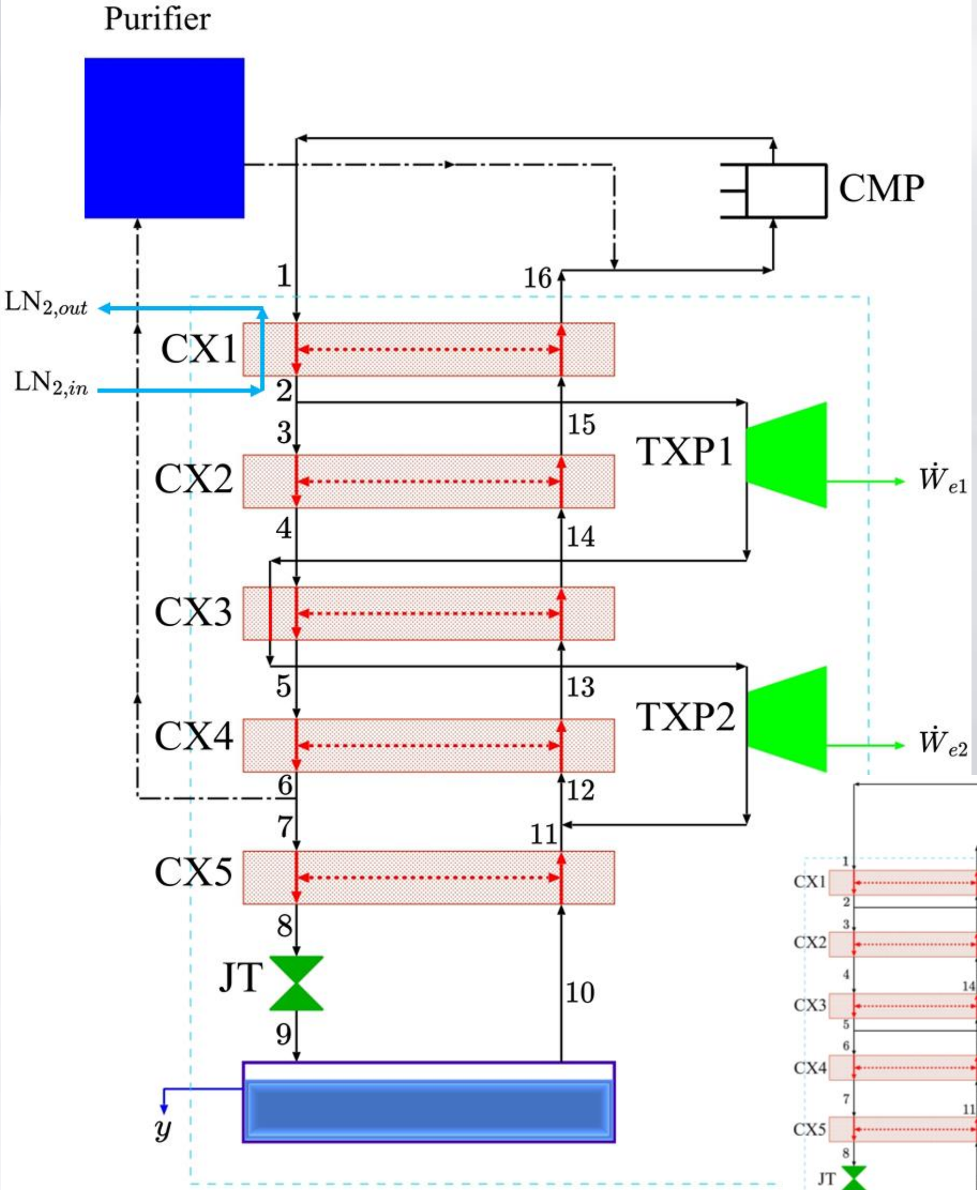
The FREIA Liquefier Schematic with Coldbox, with simplified drawing to the right

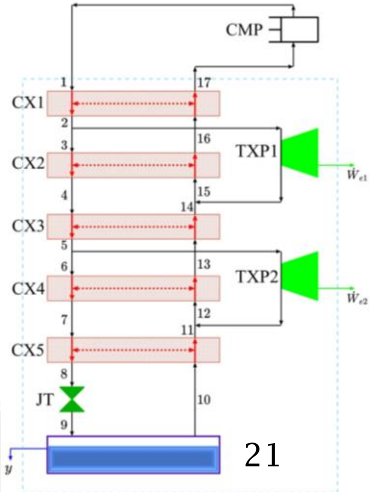
The FREIA liquefier

- Similar to Collins
- Liquid nitrogen pre-cooling system: thermal reservoir
- Single mass flow through both TXP
- 1st law around control volume

$$y \equiv \frac{\dot{m}_f}{\dot{m}} = \frac{h_{16}-h_1}{h_{16}-h_f} + \frac{\dot{m}_e}{\dot{m}}\frac{\Delta h_1+\Delta h_2}{h_{16}-h_f}$$
$$-\frac{\dot{m}_{pur}}{\dot{m}}\frac{h_6-h_{16}}{h_{16}-h_f} + \frac{\dot{m}_N}{\dot{m}}\frac{\Delta h_N}{h_{16}-h_f}$$

  - Extra terms: purification and LN2 pre-cooling

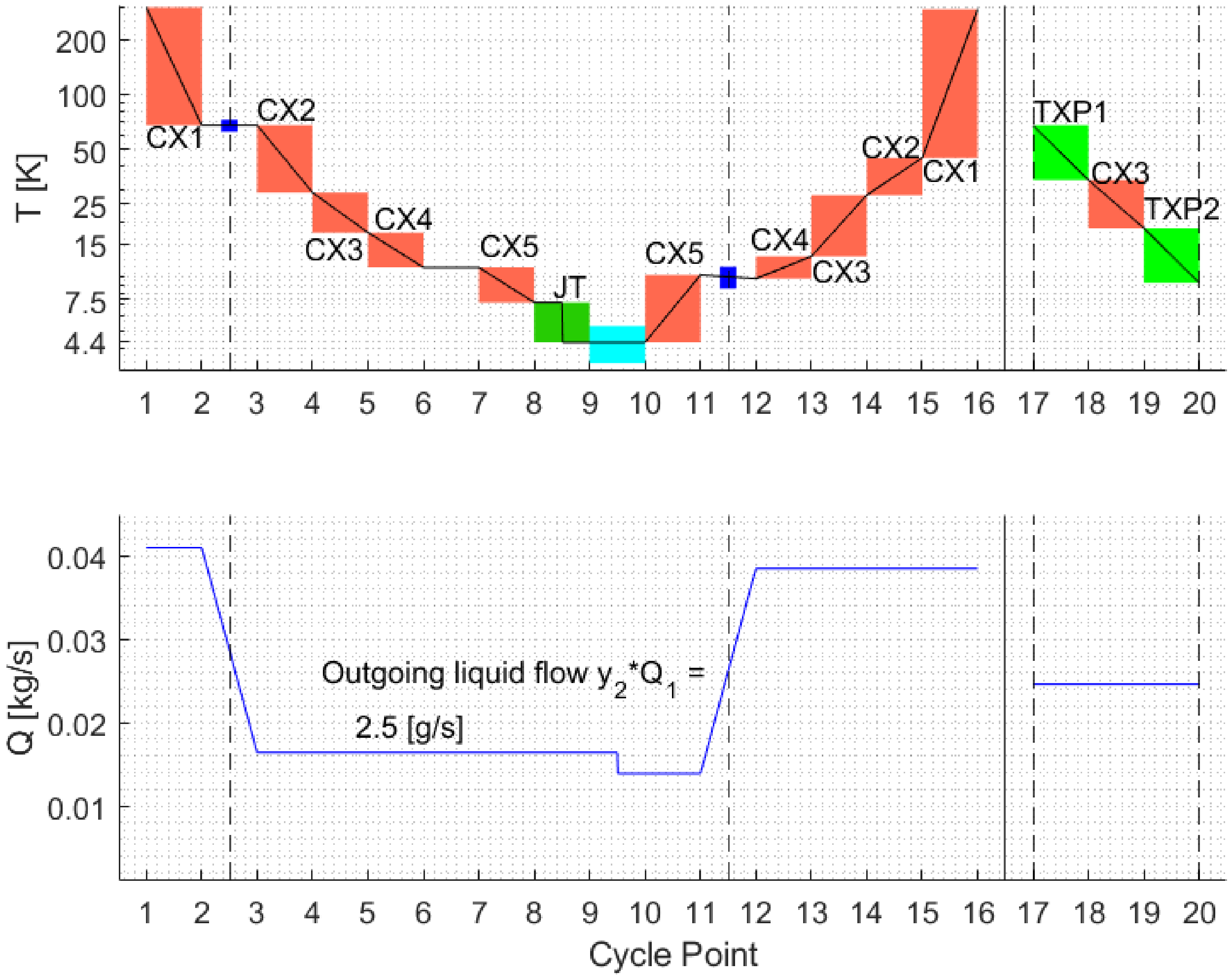




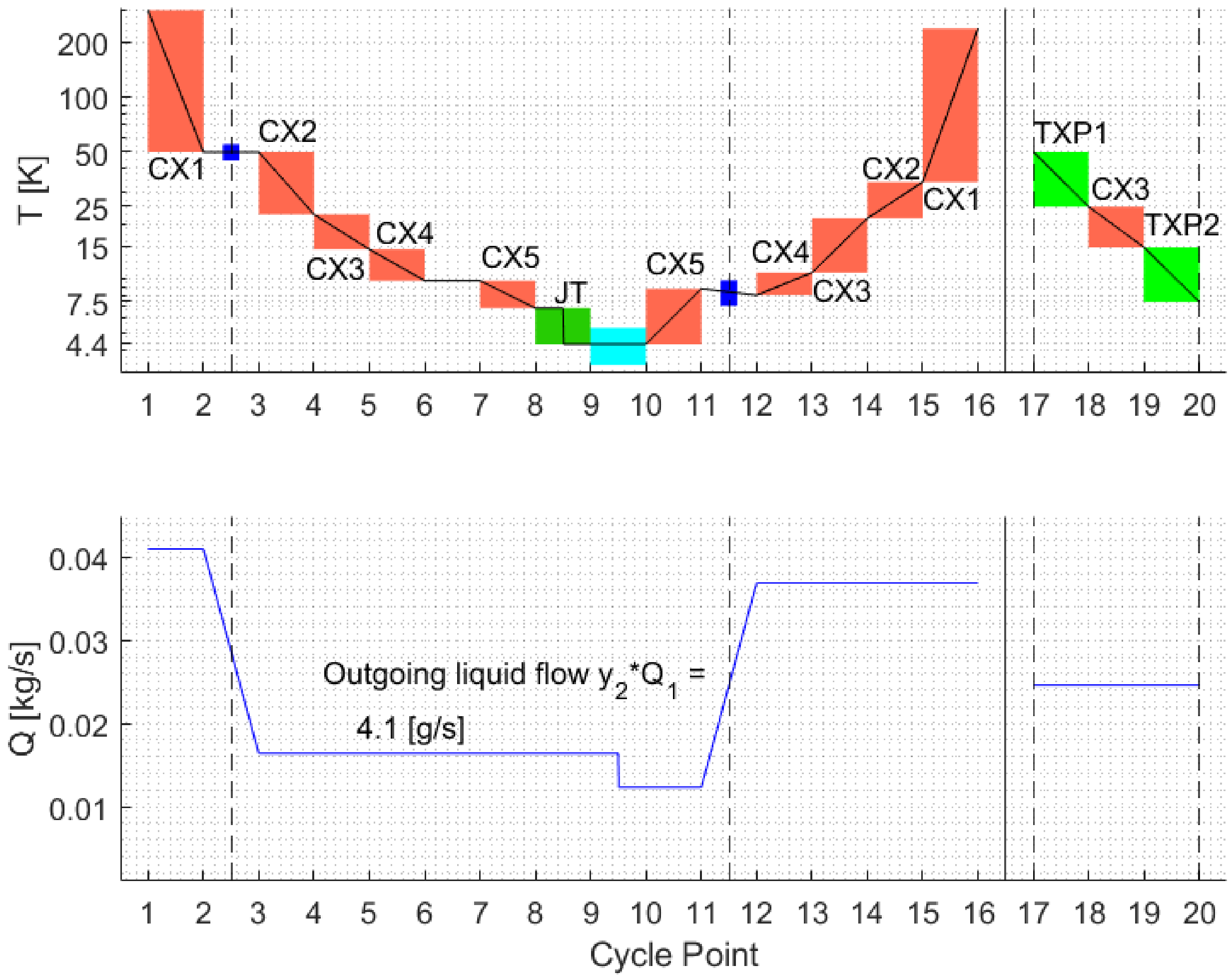
Simplified cycle of the FREIA cryosystem (vs Collins in the bottom right)

FREIA cycle simulations and results

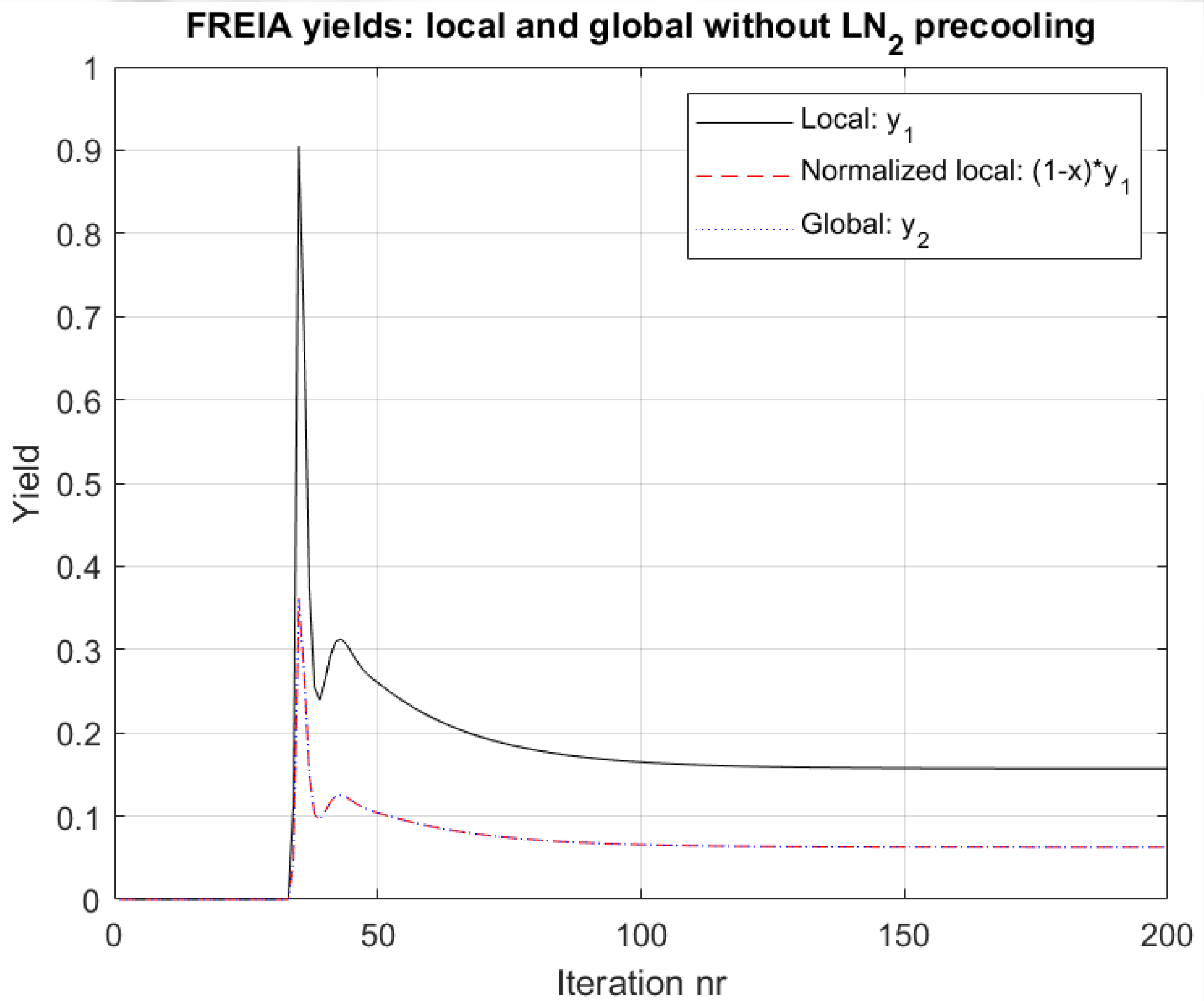
Temperature and Gas Flow Profile: FREIA without LN_2 precooling

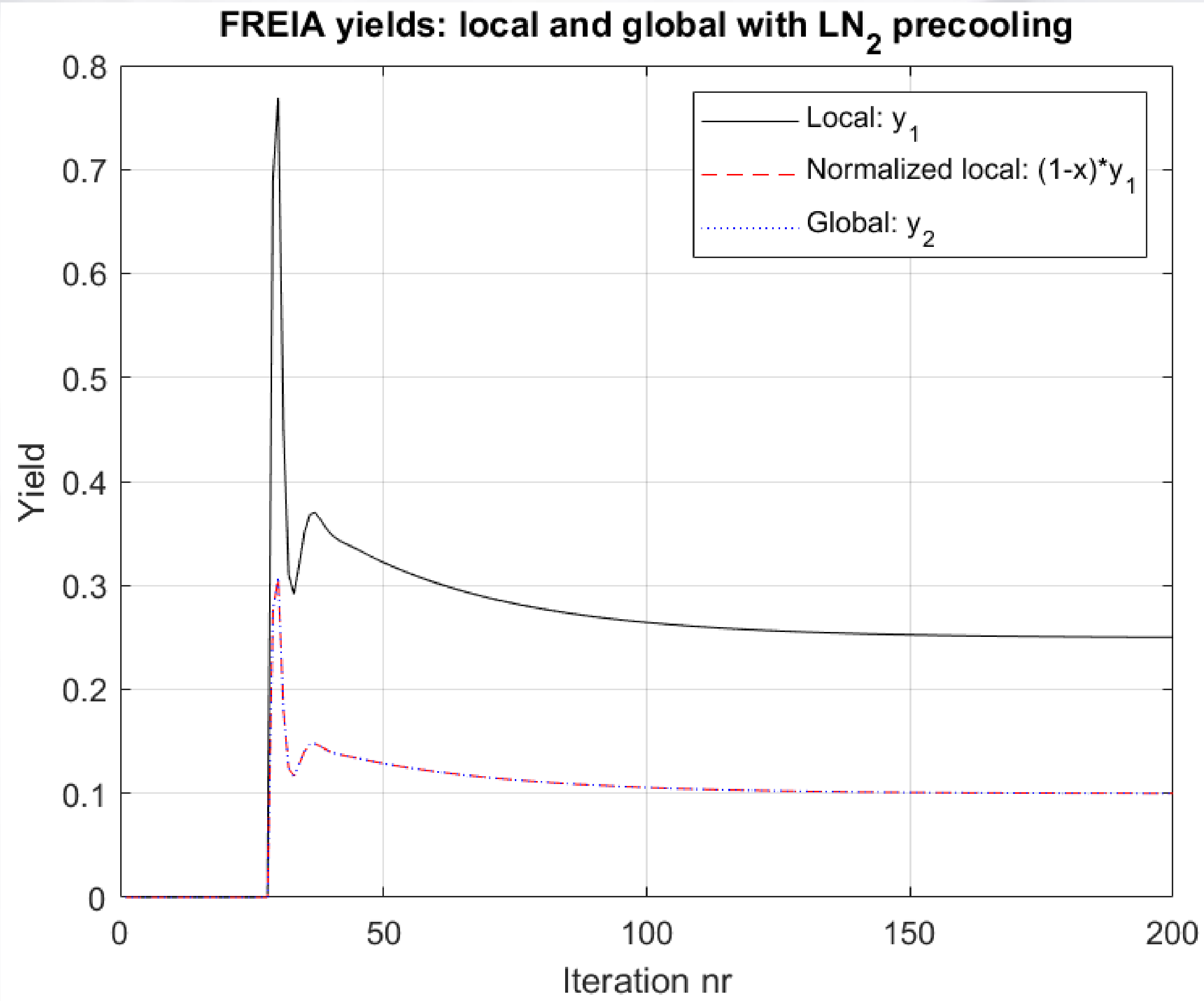


Temperature and Gas Flow Profile: FREIA with LN_2 precooling



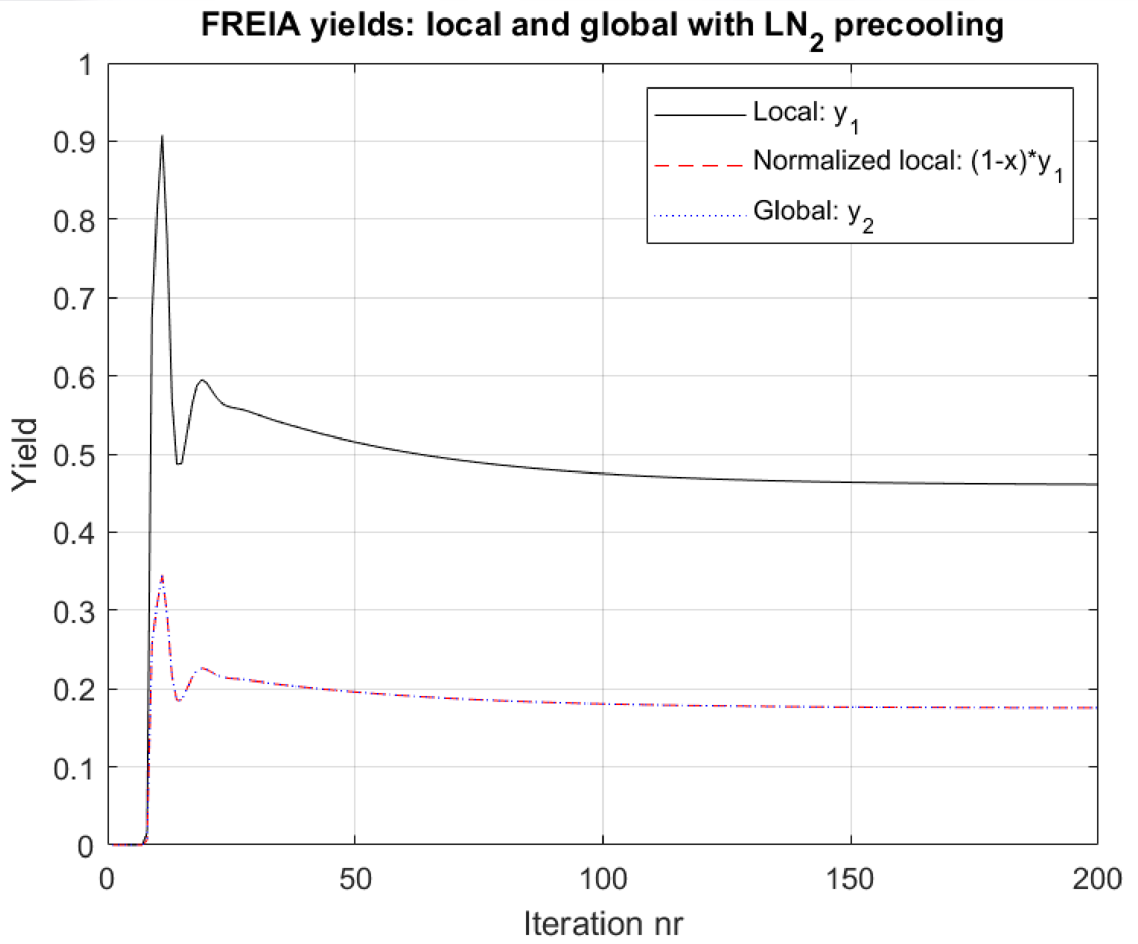
FREIA cycle simulations and results

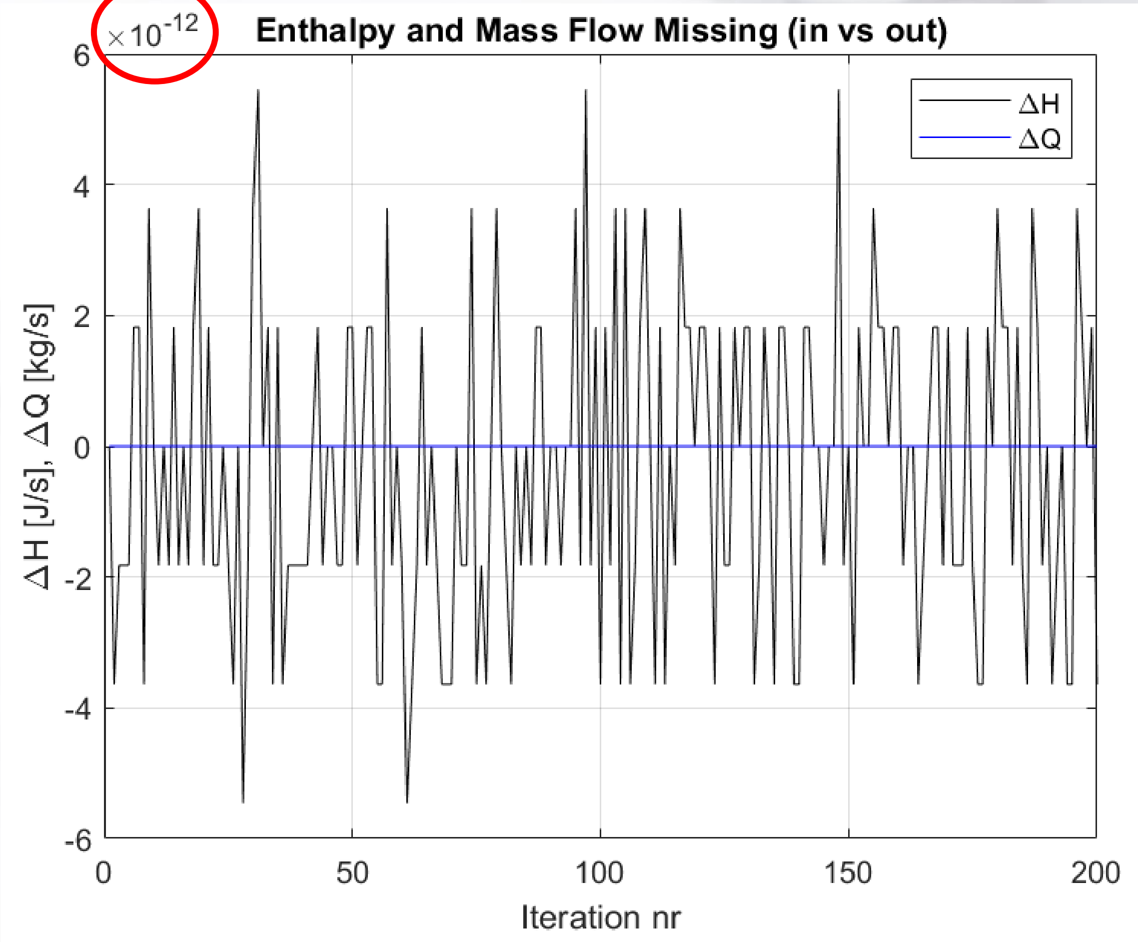




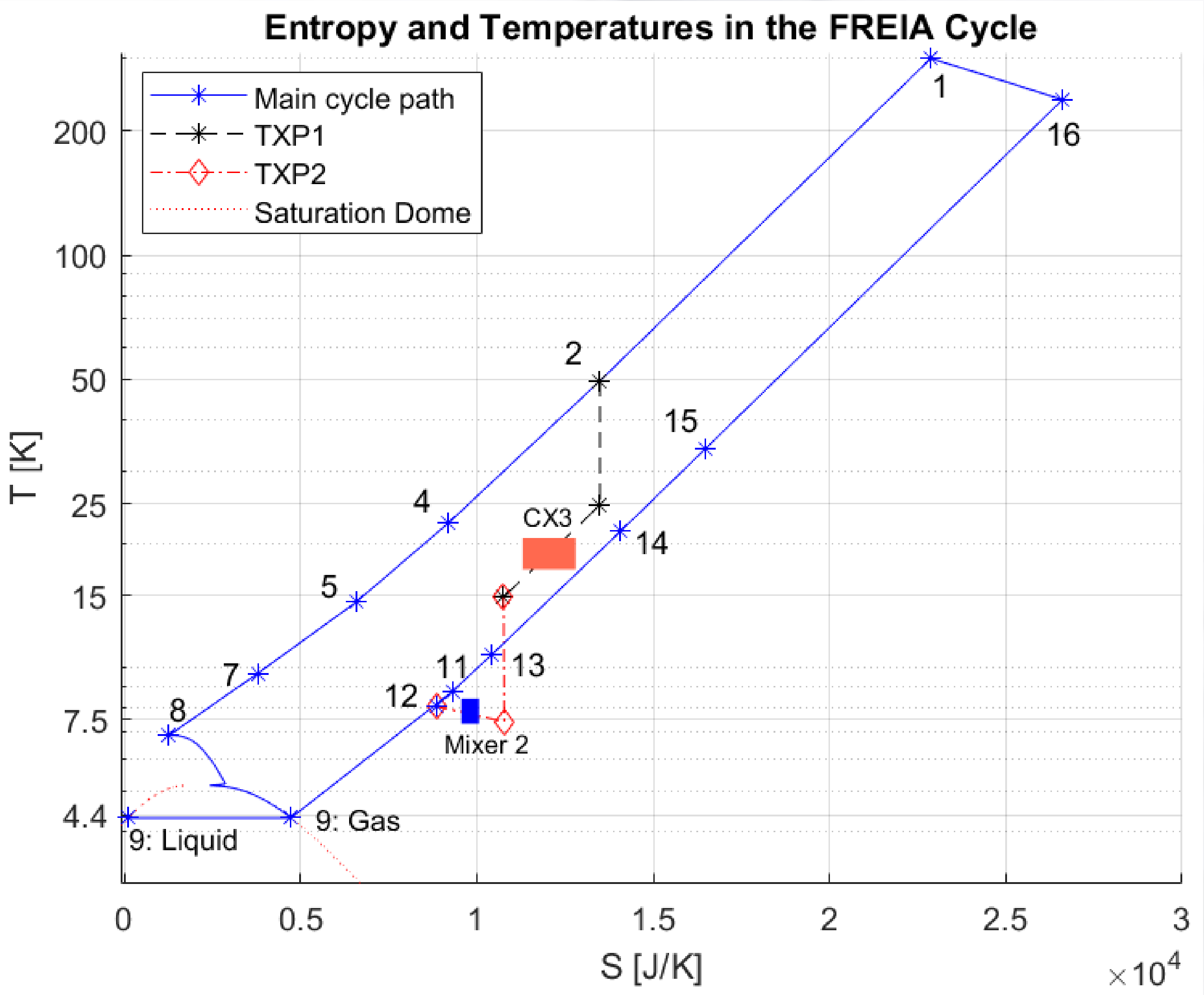
FREIA cycle simulations and results

- Maximum yield of model and sanity check



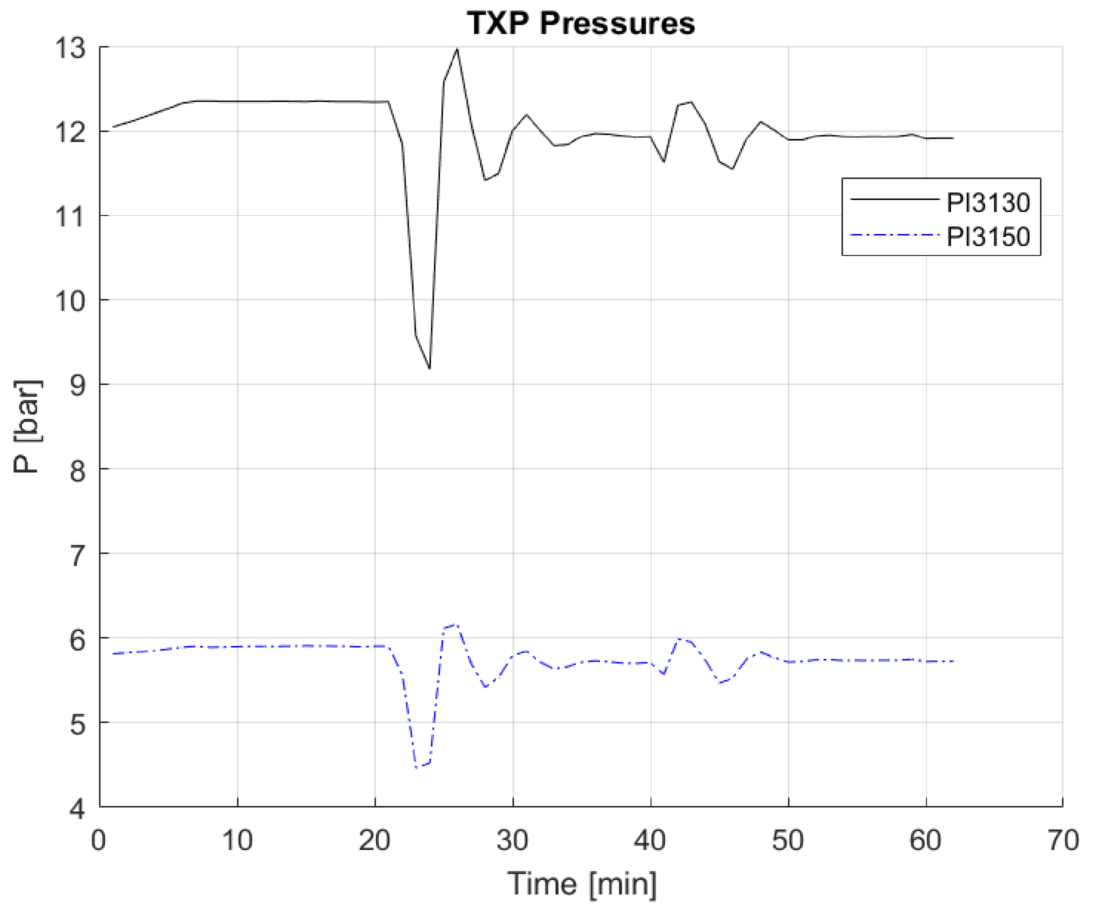


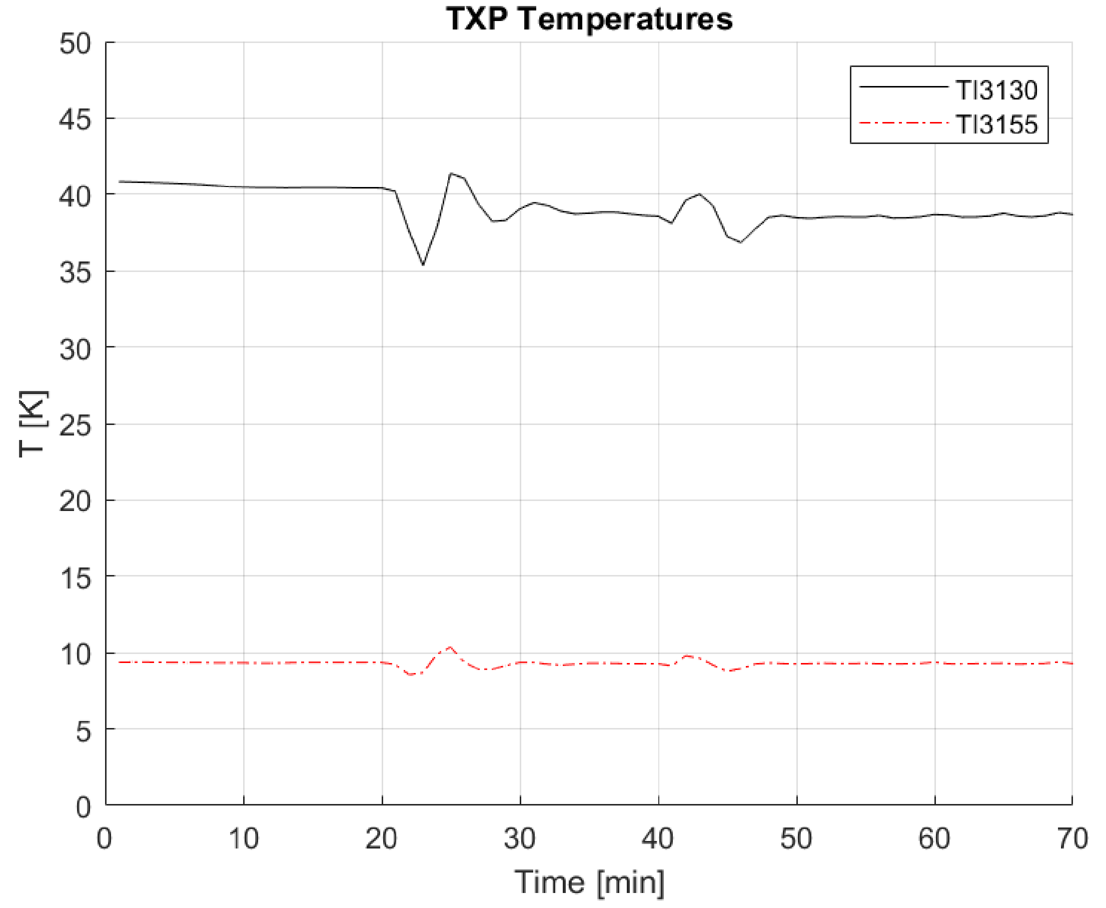
FREIA cycle simulations and results



FREIA sensor values

- Some gas to cool purification system – periodic disruption in *P* and *T*





Discussion and outlook

- Enthalpy conservation and physical processes
- Most cycle components linear
- Only liquefaction non-linear – weak non-linearity for system as a whole
- Yield of model simulation close to yields of real liquefier
- Maximum yield of model – mainly tune heat exchanger design parameter C'

Discussion and outlook

- Turboexpanders not entirely isentropic
- Specific heat capacity c_P not constant for last heat exchanger
- Importance of optimized liquefaction cycles
- More sensors for future comparisons?

Thank you for your attention!