Midterm presentation - Benchmarking a Cryogenic Code to the FREIA 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

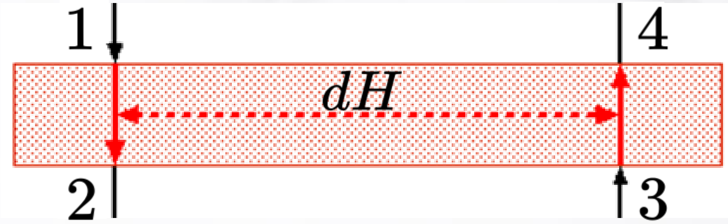
Linde liquid He production and recovery system – linde-engineering.com

Some thermodynamic concepts

- Enthalpy

$$H = U + pV, \qquad U = U(T) \text{ for ideal gas}$$

- Joule-Thomson (JT) valve
  - Irreversible, isenthalpic process: $\Delta H = 0$
  - Inversion temperature
- Enthalpy in heat exchanger



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

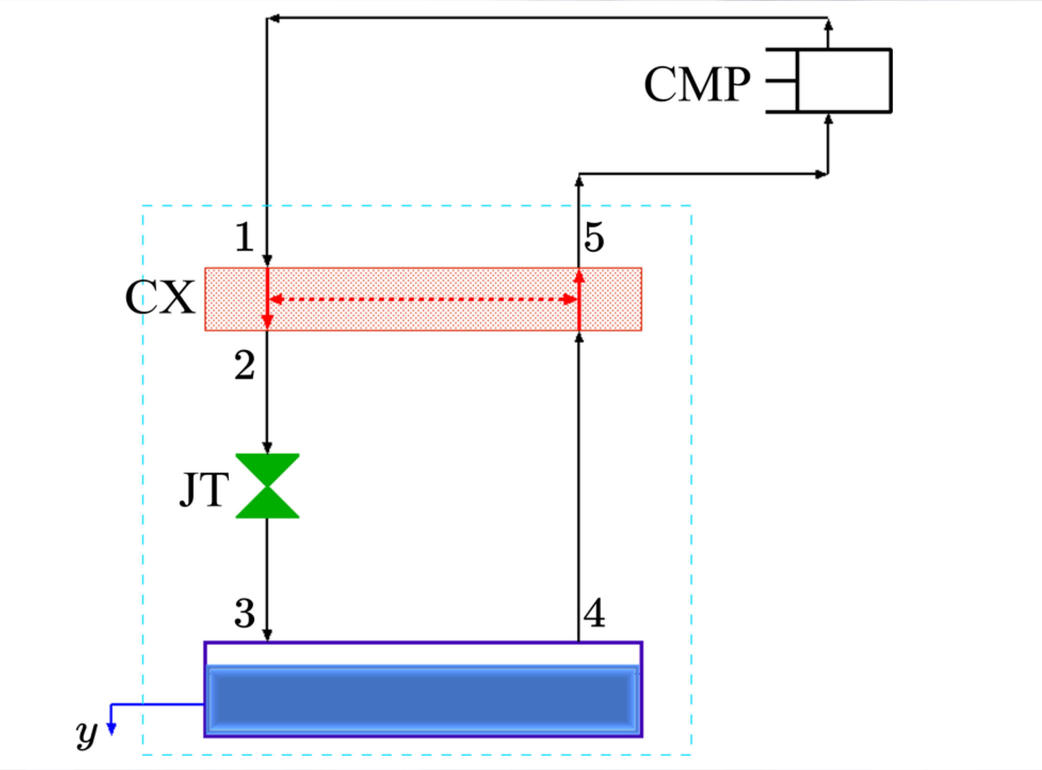
Liquefaction cycles - Linde

- Most fundamental cycle, 1895
- 1st law of thermodynamics in control volume (dashed):

$$\dot{m}h_1 = \dot{m}_f h_f + (\dot{m} - \dot{m}_f)h_5$$
$$\Leftrightarrow \dot{m}h_2 = \dot{m}_f h_f + (\dot{m} - \dot{m}_f)h_4$$

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

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



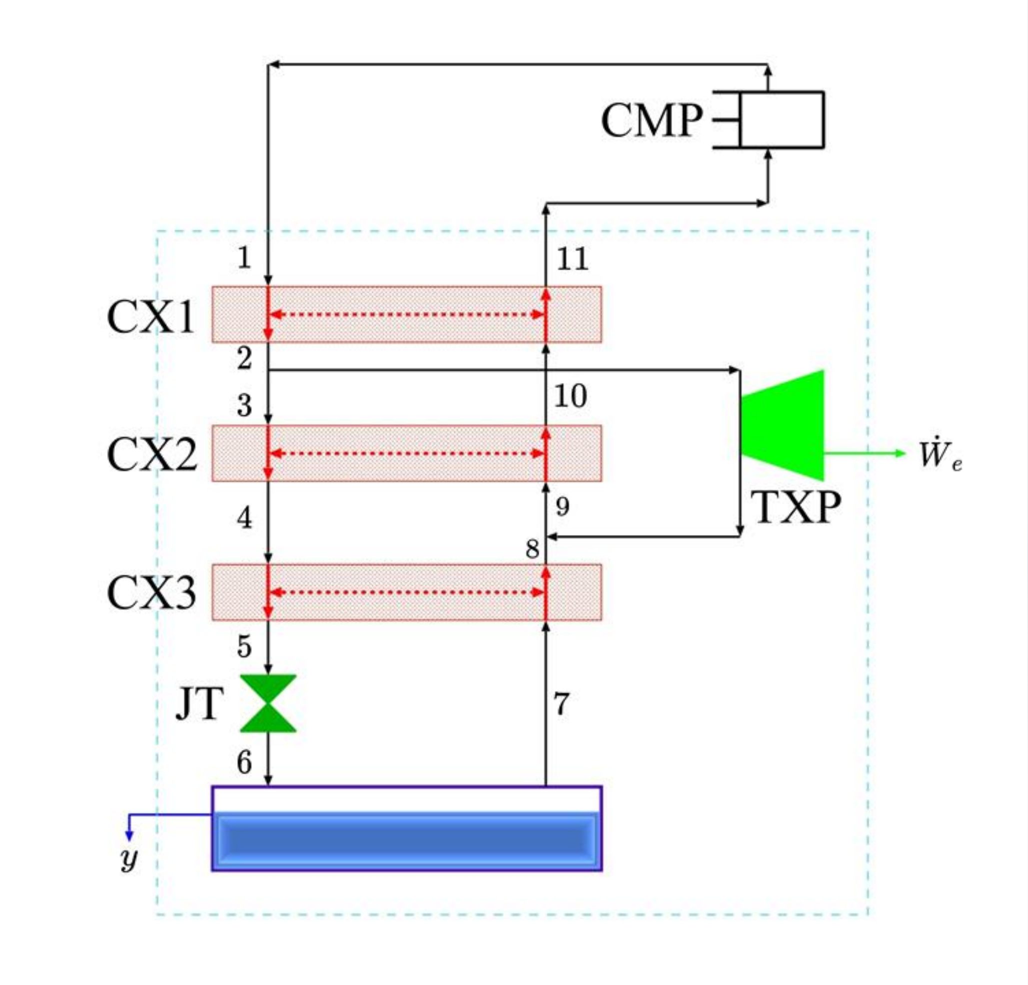
Liquefaction cycles - Claude

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

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

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

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



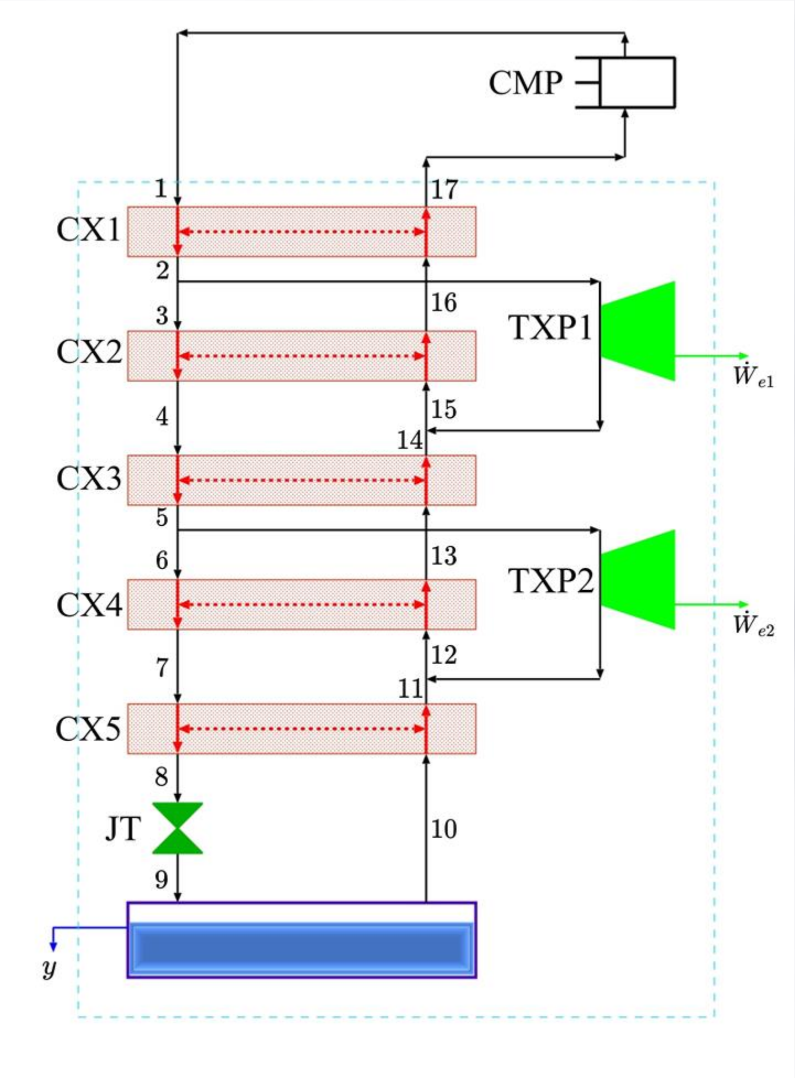
Liquefaction cycles - Collins

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

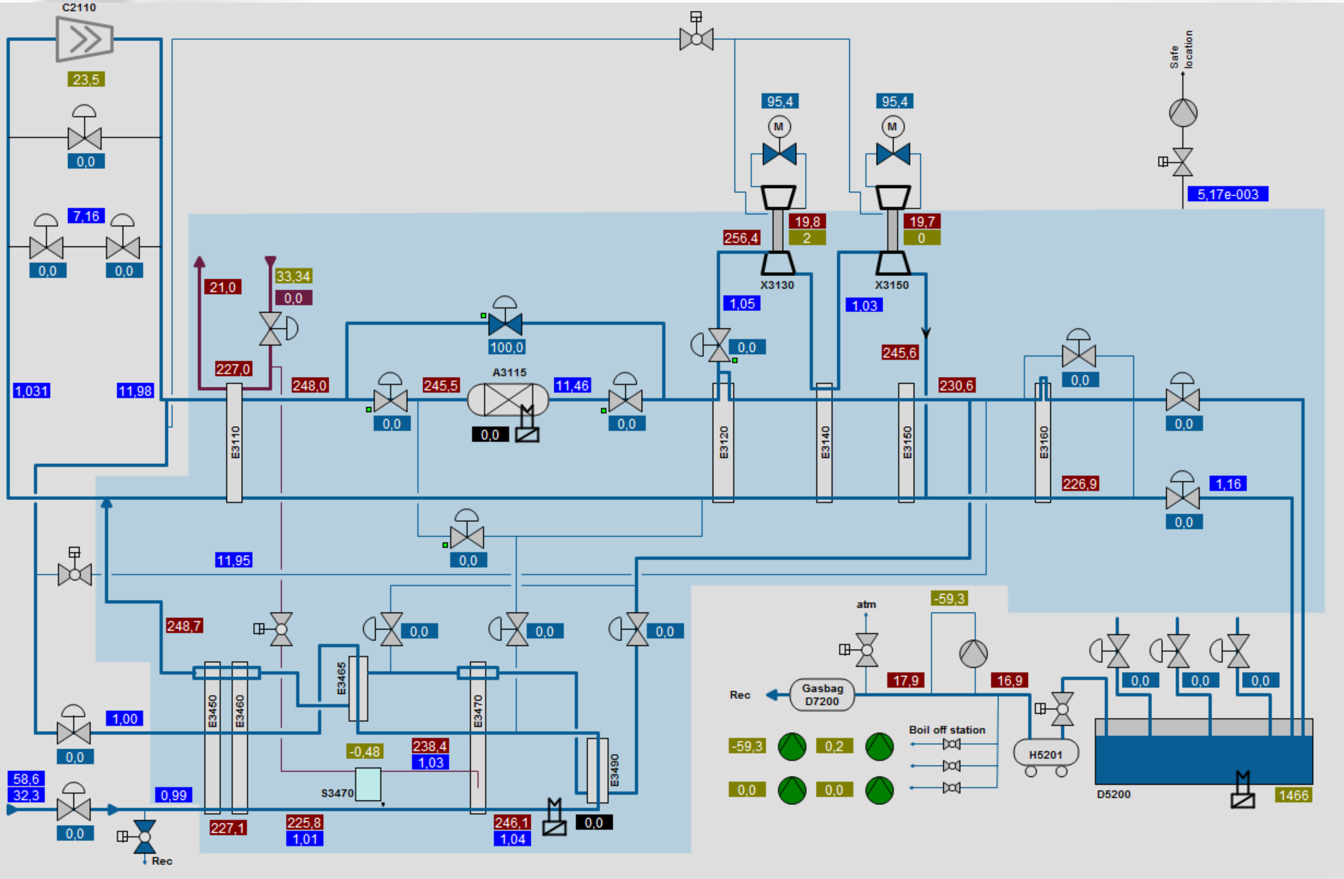
$$y \equiv \frac{\dot{m}_f}{\dot{m}} = \frac{h_{17}-h_1}{h_{17}-h_f} + x_1 \frac{\Delta h_{e1}}{h_{17}-h_f} + x_2 \frac{\Delta h_{e2}}{h_{17}-h_f}$$

with

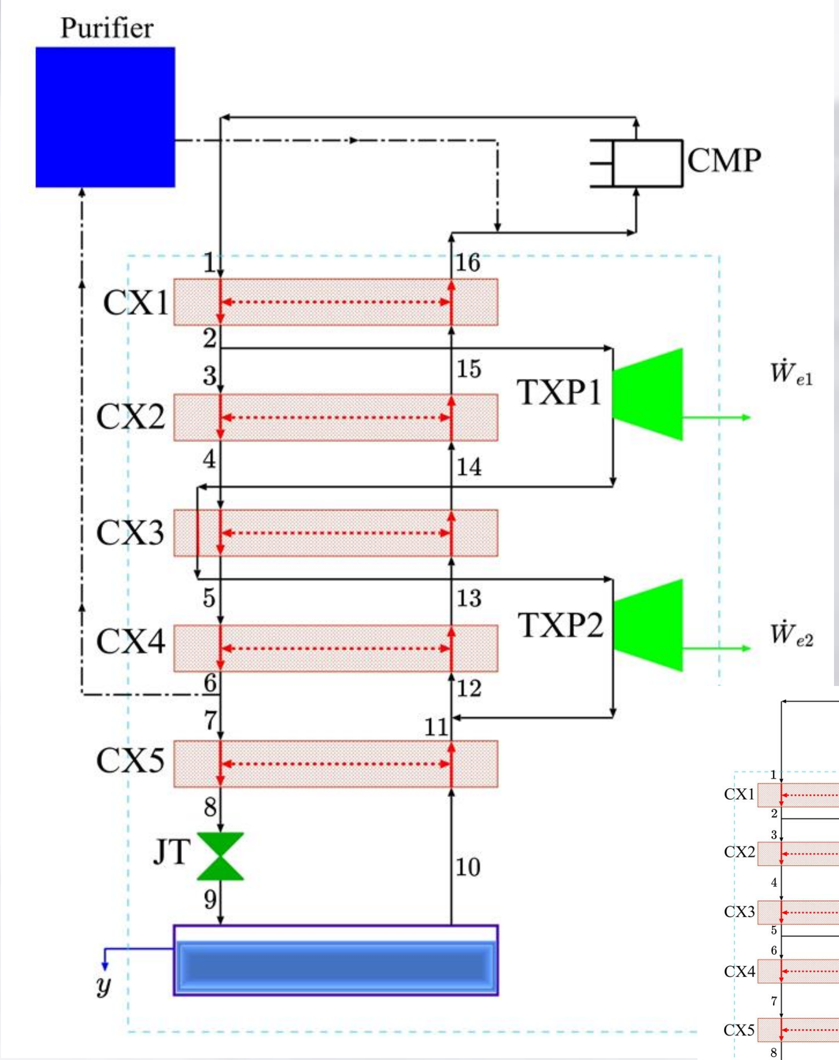
$$\dot{W}_{e_i} = \dot{m}_{e_i} \Delta h_{e_i} \qquad x_i = \frac{\dot{m}_{e_i}}{\dot{m}}, \qquad i = 1, 2$$



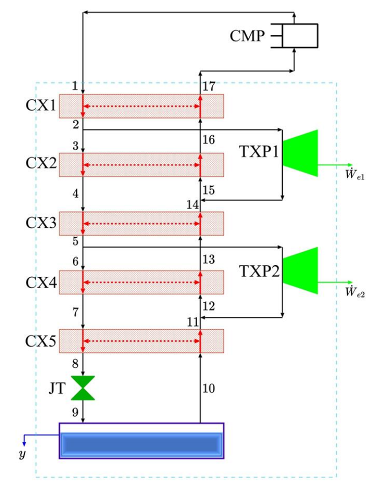
The FREIA System



The FREIA Liquefier Schematic with Coldbox



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

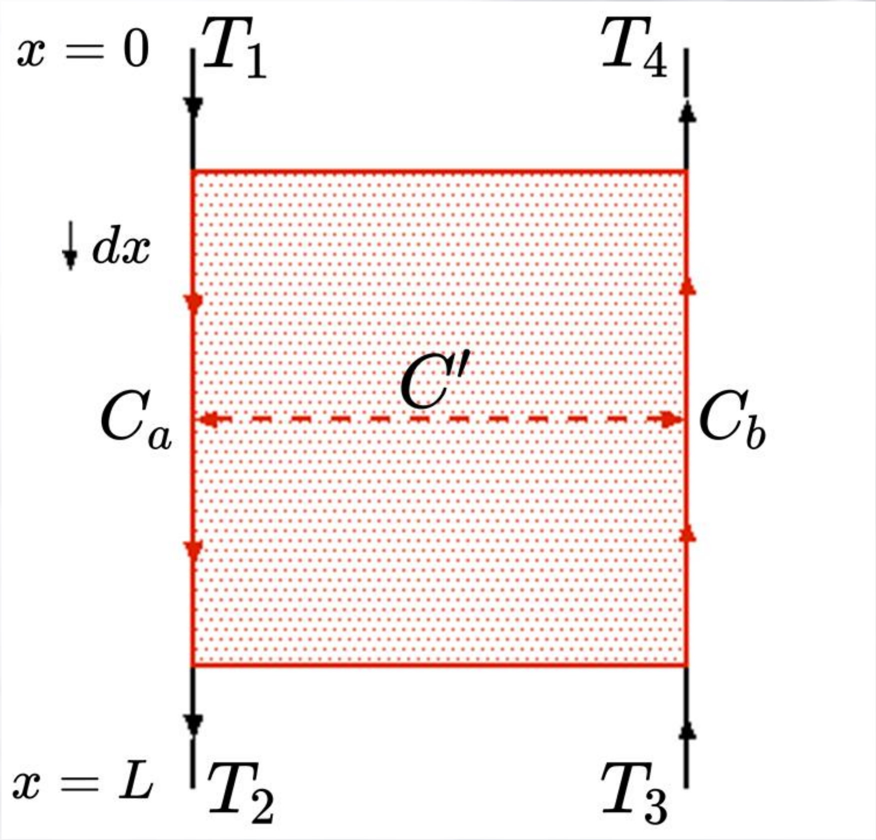


Cycle components: counterflow heat exchanger

- System of linear equations

$$T_2 = T_1 - \eta(T_1 - T_3) \qquad \eta = \frac{1-e^{-\alpha}}{1-\frac{\dot{m}_a c_a}{\dot{m}_b c_b} e^{-\alpha}}$$

$$T_4 = T_3 + \frac{\dot{m}_a c_a}{\dot{m}_b c_b}\eta(T_1 - T_3)$$



- Enthalpy transfer

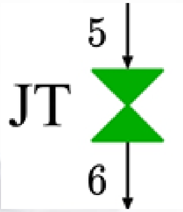
$$\Delta\dot{H} = C_H(T_3 - T_1)$$

$$C_H = \frac{C_a C_b(1-e^{-\alpha})}{C_a e^{-\alpha} - C_b} \qquad (C_a \neq C_b)$$

$$\frac{1}{C_H} = \frac{1}{C_a} + \frac{1}{C'L} \qquad (C_a = C_b)$$

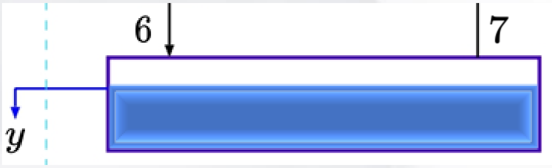
Cycle components – MatLab implementation

- JT valve:



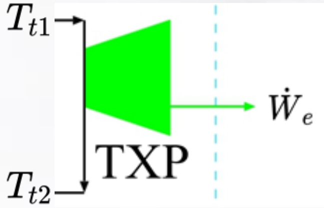

```
%JT-valve - isenthalpic process
T5= py.CoolProp.CoolProp.PropsSI('T','P',Phigh*1e5,'H',H5/Q5,'Helium');
H6 = H5;
Q6 = Q5;
T6= py.CoolProp.CoolProp.PropsSI('T','P',Plow*1e5,'H',H6/Q6,'Helium');
```

- 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;
```

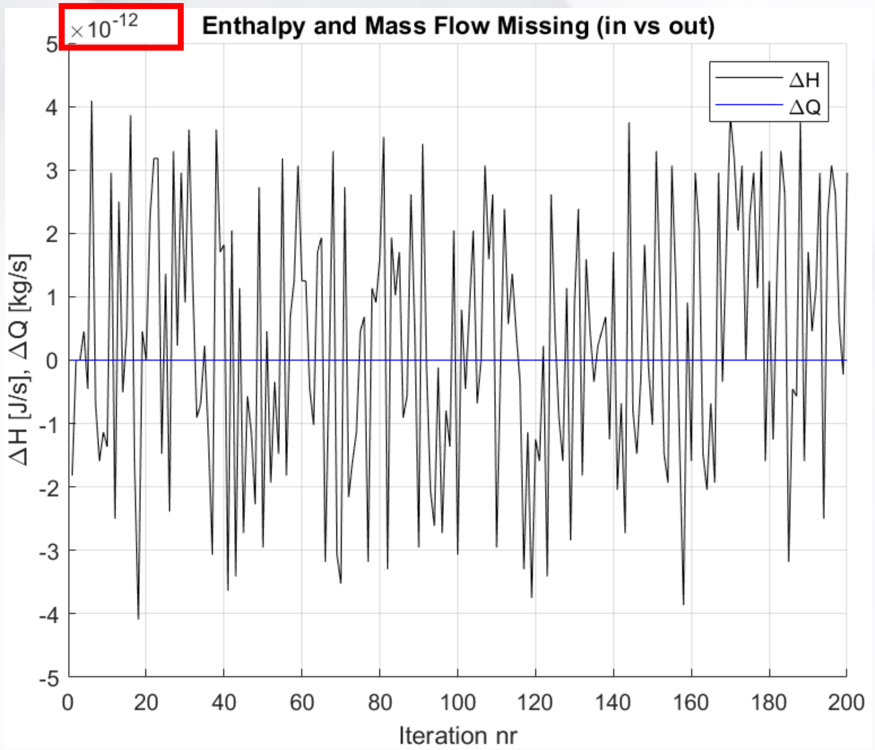
- Turboexpander:

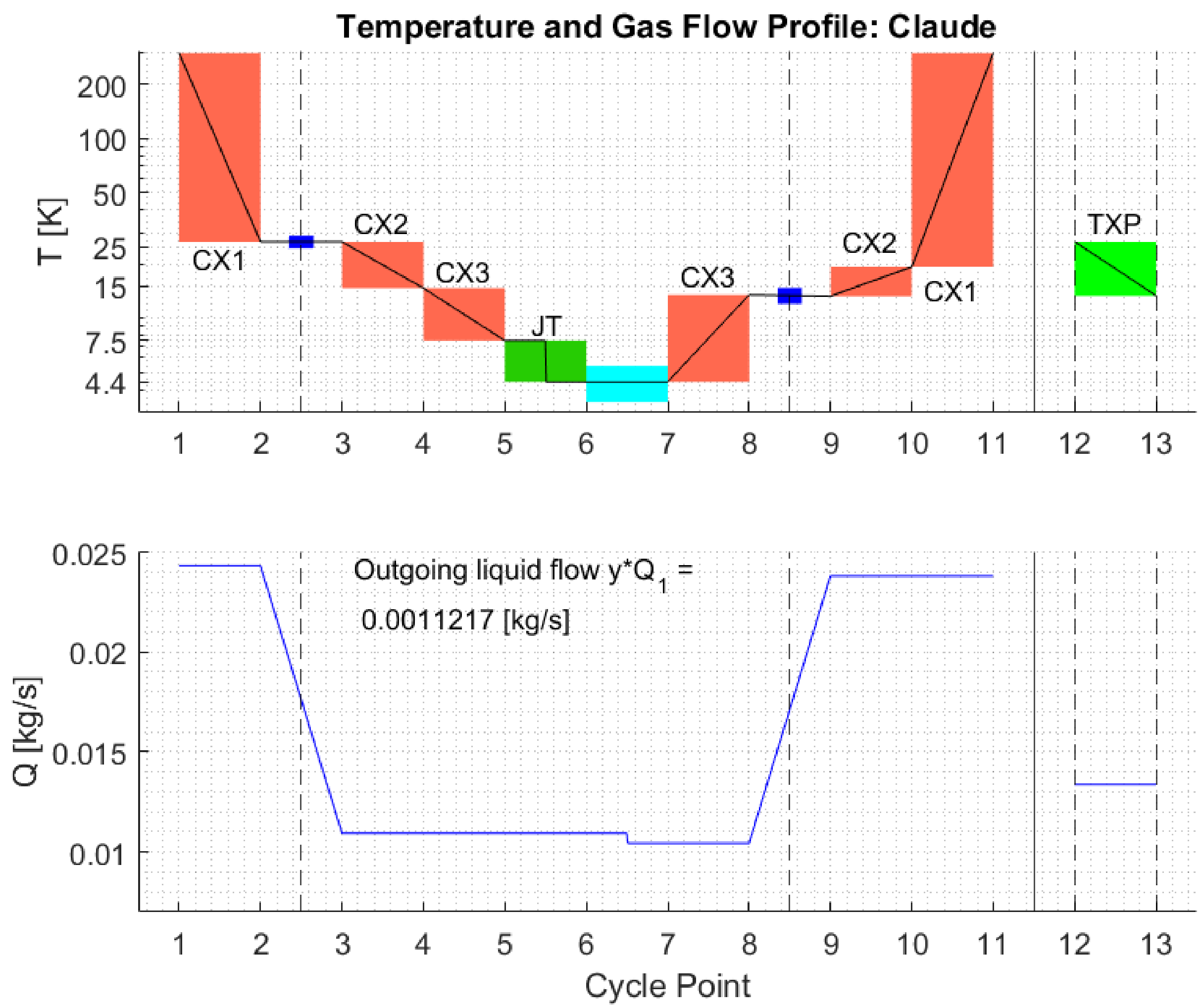



```
Ht1 = x*H2;
Tt1 = T2;
Tt2 = 0.5*T2;
Pt2 = Phigh/5.64;
ht2 = py.CoolProp.CoolProp.PropsSI('H','P',Pt2*1e5,'T',Tt2,'Helium');
Ht2 = x*Q1*ht2;
W = Ht1 - Ht2;
```

Simulations so far - Claude

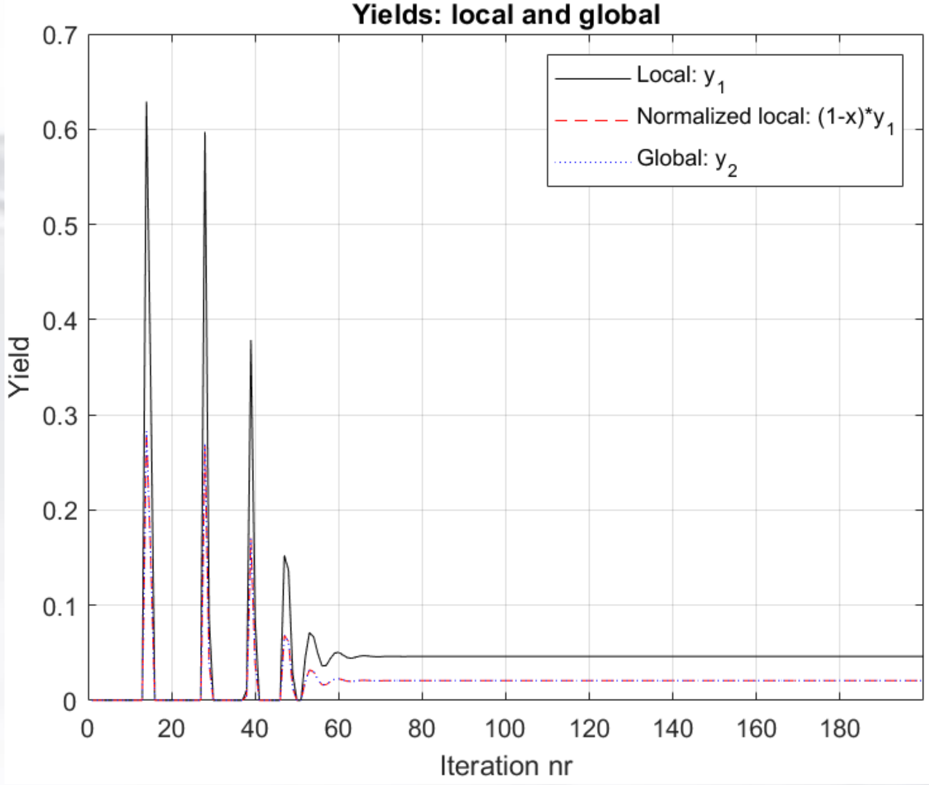
- Iterative tester with MatLab function – convergence
- Enthalpy and mass flow conservation

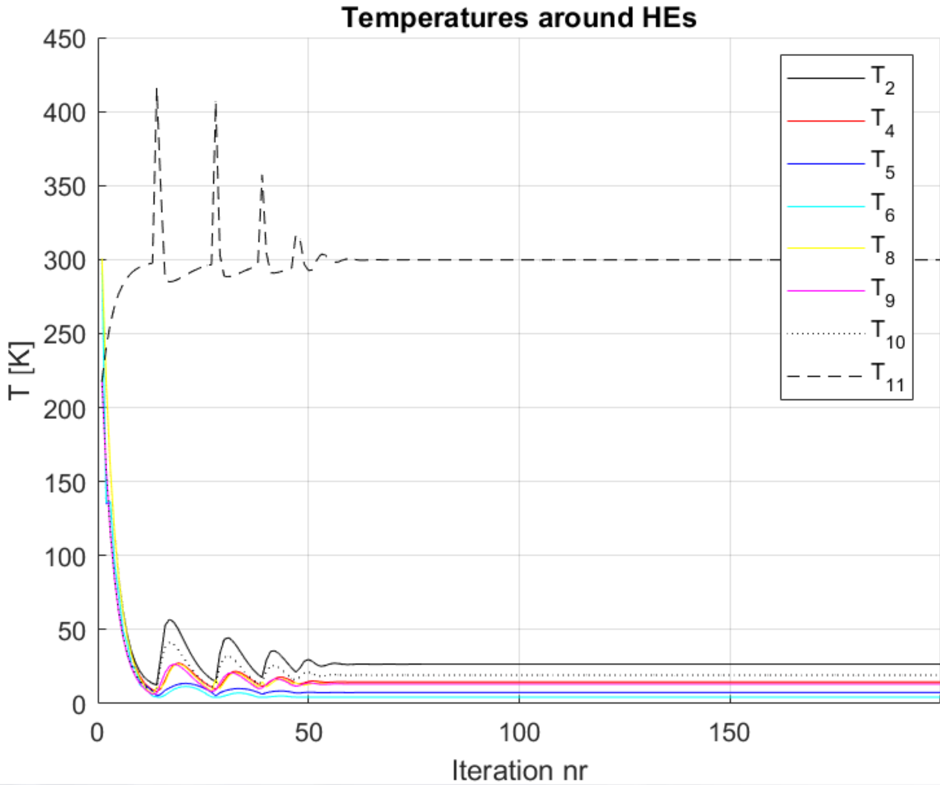




Next steps

- Oscillatory behaviour
- Convergence to low yields
- Implement the FREIA schematic
- Three-way heat exchanger
- Use actual T and P sensor values (if possible)





Thank you for your attention!