Optimization of a Single Expander LNG Process

Bjørn Austbø and Truls Gundersen
Department of Energy and Process Engineering
Norwegian University of Science and Technology (NTNU)

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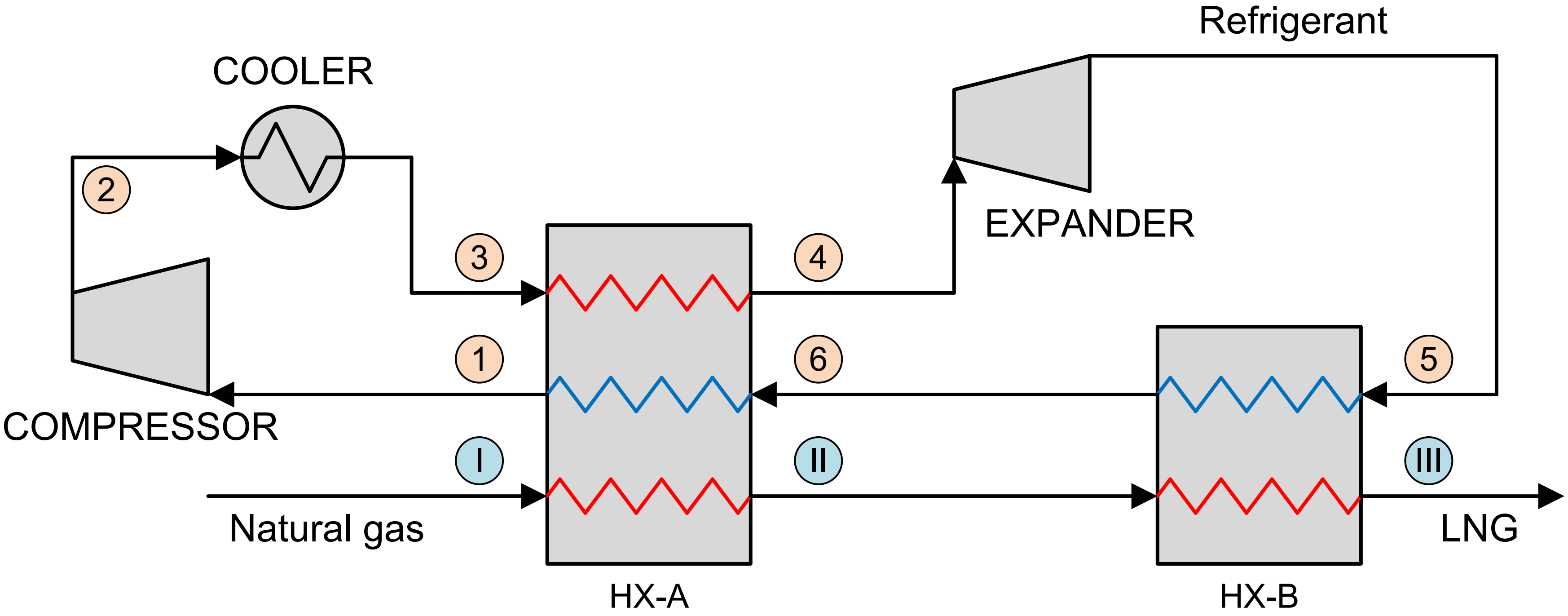
Single expander LNG process



Outline

- Motivation
- Problem formulation
- Simplified model
- Rigorous model
- Comparison
- Conclusions

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Motivation – floating LNG

- Criteria for selection of liquefaction technology (Tangen and Mølnvik, 2009; Castillo and Dorao, 2010):
  - Profitability
  - Energy efficiency
  - Environmental impact
  - Safety
  - Operability
  - Compactness
  - Equipment count
  - Motion impact
- Expander processes an interesting alternative

Motivation – expander processes

- Remeljej and Hoadley (2006) performed an exergy analysis of a dual expander process for natural gas liquefaction using the Peng-Robinson equation of state for modelling

- Shah and Hoadley (2007) proposed a shaftwork targeting method for expander processes with applications in natural gas liquefaction

- Marmolejo-Correa and Gundersen (2013) used an exergy diagram for targeting and design of a single expander process assuming ideal gas behaviour

Motivation

- Is a perfect gas model accurate for design and optimization of a single expander process for natural gas liquefaction?

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Problem formulation

- Optimization problem:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \dot{W}_{\text{NET}}(\mathbf{x}) = \dot{W}_{\text{COMP}}(\mathbf{x}) - \dot{W}_{\text{EXP}}(\mathbf{x}) \\ \text{s.t.} \quad & \Delta T_{\text{HX}}(\mathbf{x}) \geq \Delta T_{\text{min}} \end{aligned}$$

- Constant isentropic efficiency:
  - Compressor: $\eta_{\text{s,COMP}}$
  - Expander: $\eta_{\text{s,EXP}}$

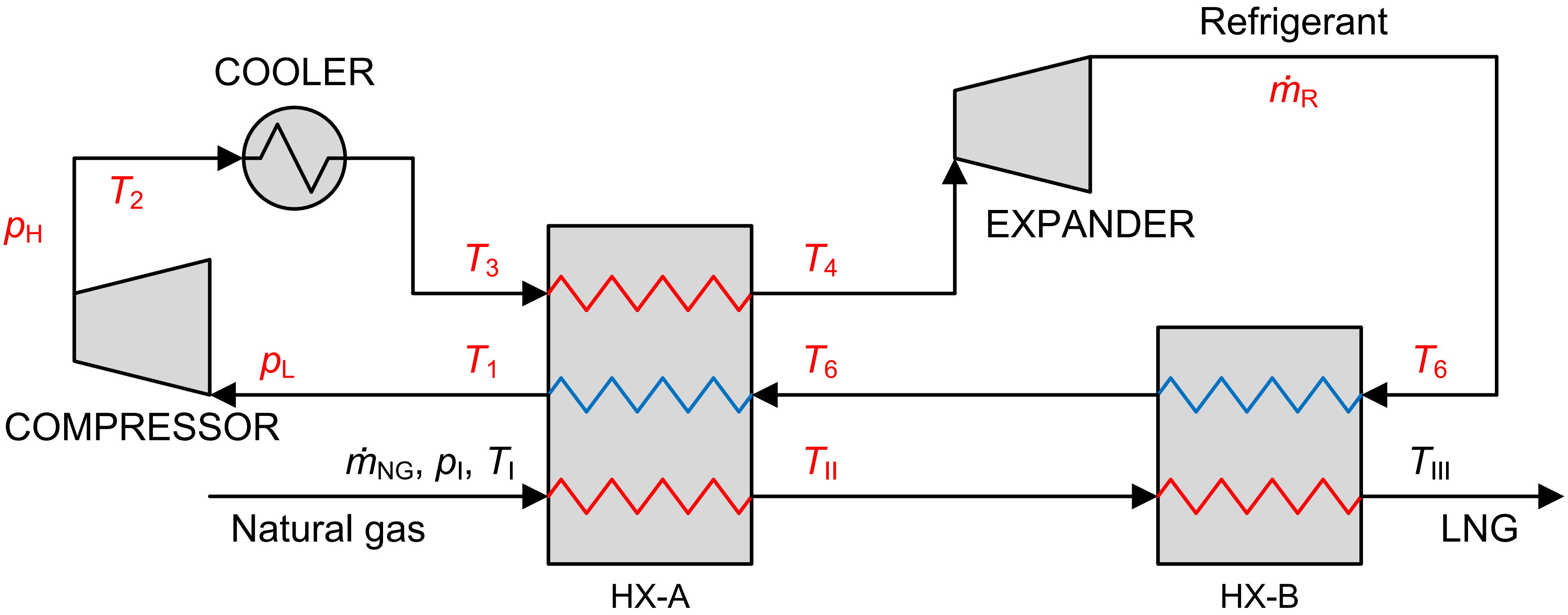
- Refrigerant: nitrogen

Problem formulation

- Process specifications – natural gas:

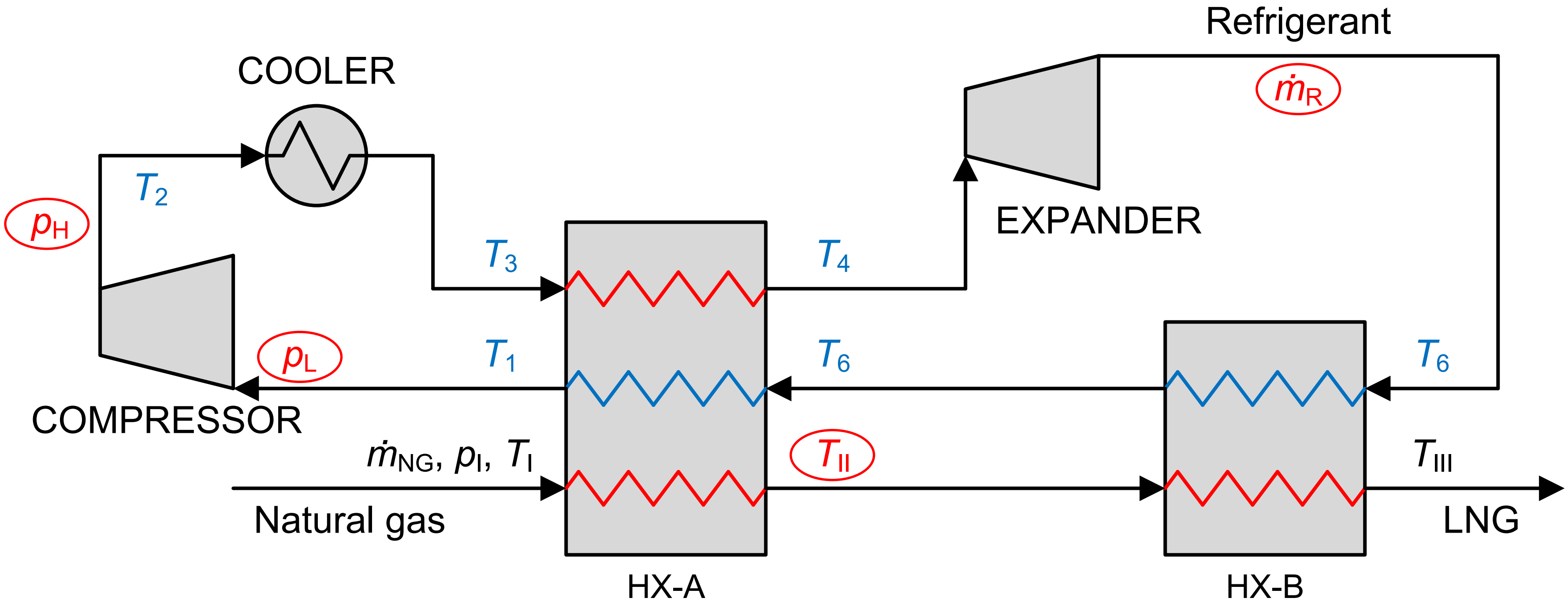
Variable	Unit	Value
Flow rate	kg/s	1
Feed pressure	bar	55
Feed temperature	K	293.15
Product temperature	K	115.00
Molar composition:		
Methane	-	0.897
Ethane	-	0.055
Propane	-	0.018
N-butane	-	0.002
Nitrogen	-	0.028

Problem formulation



- Uniform heat exchanger exit temperature ($T_4 = T_{II}$)
- Given cooler temperature ($T_3 = T_I$)
- Two heat exchanger energy balances
- Compressor equation
- Expander equation

Problem formulation



Four degrees of freedom for design optimization

Problem formulation

Simplified model:

- Perfect gas model (ideal gas + constant $c_{p,R}$)
- Mean natural gas heat capacity $(\dot{m} \cdot c_p)_{NG}$
- Solved analytically

Rigorous model:

- Soave-Redlich-Kwong equation of state
- Process modelling: Aspen HYSYS® (Aspen Technology, Inc.)
- Optimization: Sequential quadratic programming, NLPQLP (Schittkowski, 2006)

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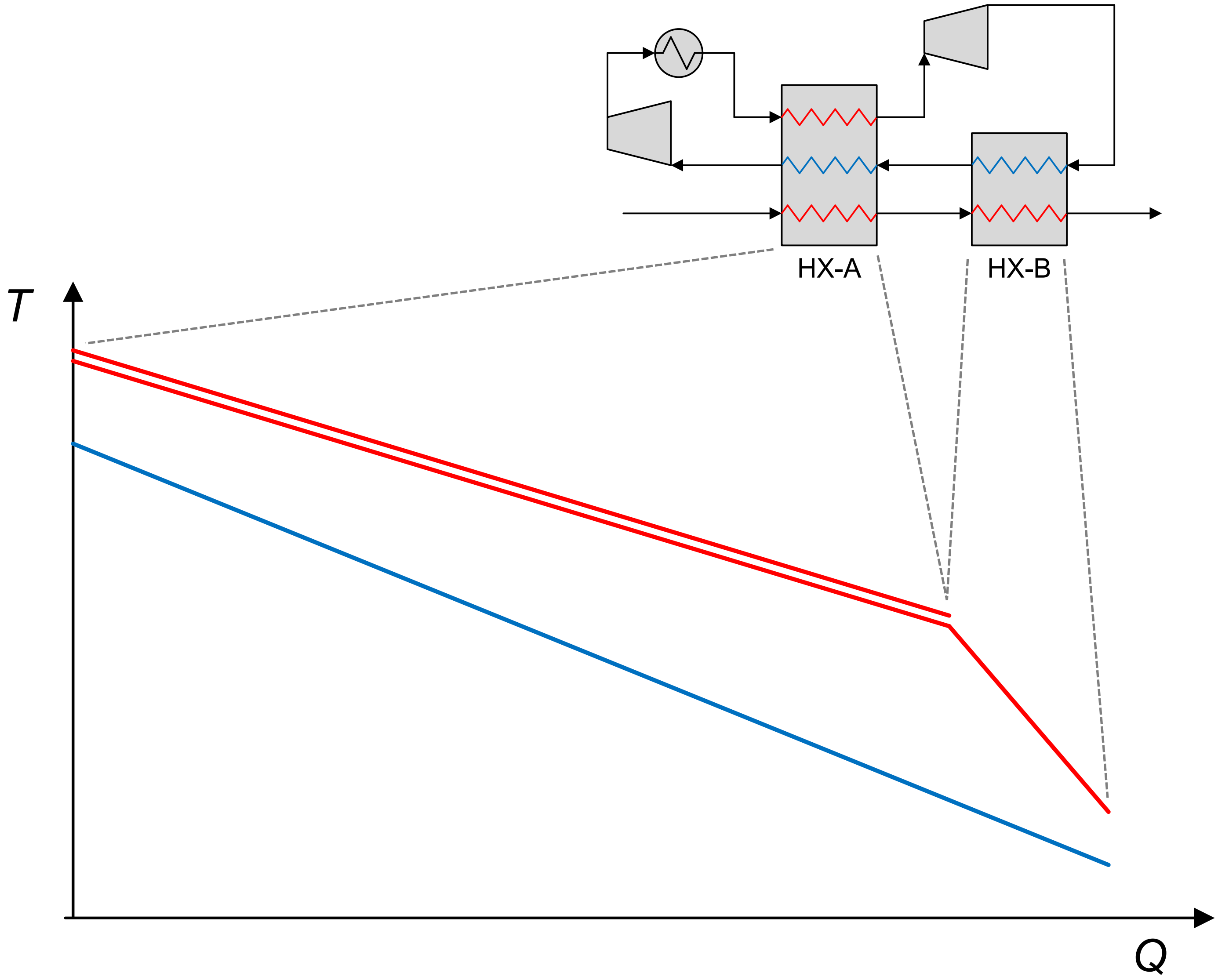
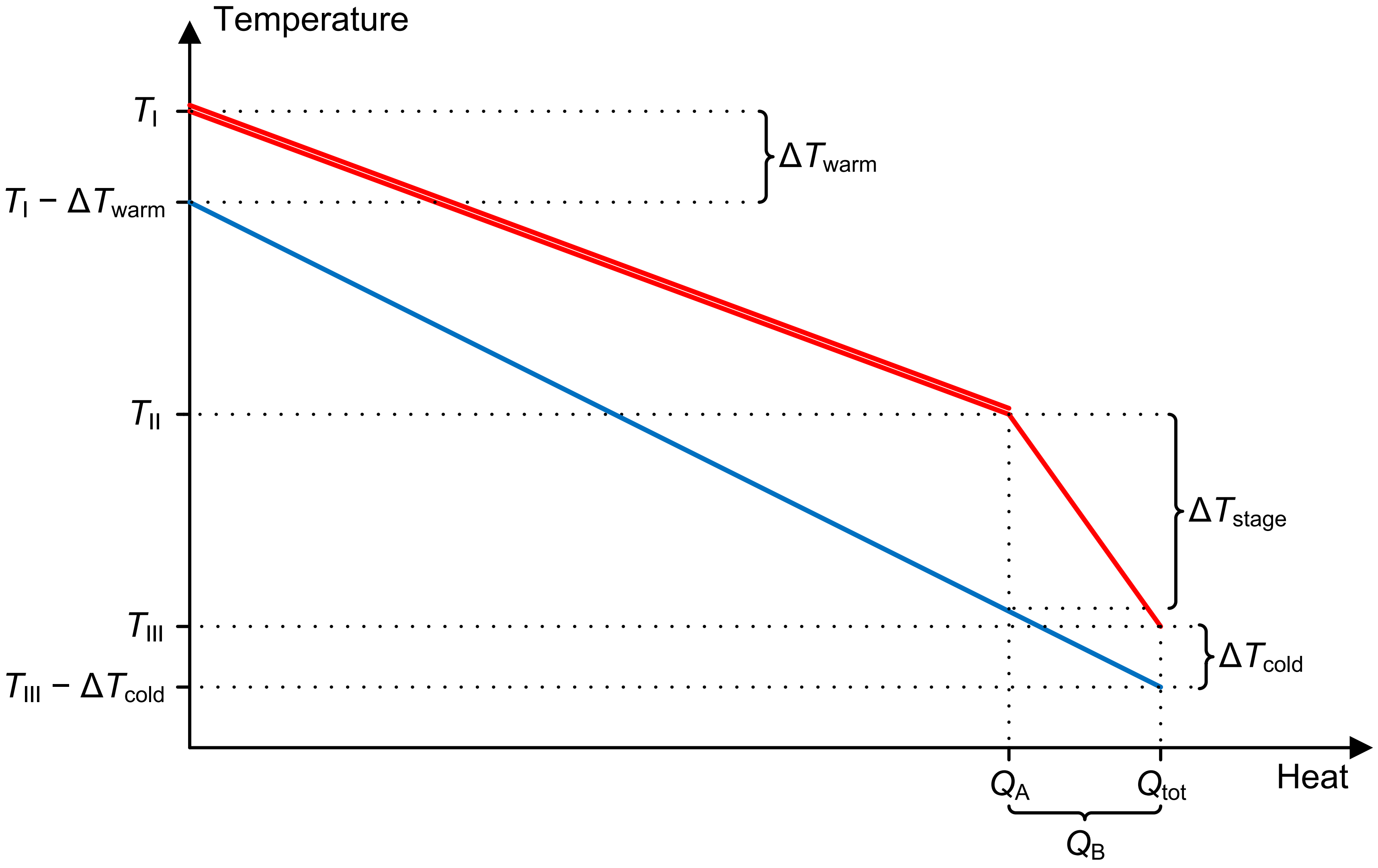
Simplified model



Simplified model



Simplified model

- Decision variables:
  - Stage temperature T_{II}
  - Cold end temperature difference $\Delta T_{\mathrm{cold}} = T_{\mathrm{III}} - T_5$
  - Warm end temperature difference $\Delta T_{\mathrm{warm}} = T_{\mathrm{I}} - T_1$
  - Pressure level p_{L} or p_{H}
    (does not influence power consumption)

Simplified model

- Calculations:
  - Energy balance for the heat transfer process
  - Equation for the compression process
  - Equation for the expansion process
  - Definition of isentropic efficiency
  - Equation for entropy change for ideal gas

→ Net power consumption as a function of the decision variables:

$$\dot{W}_{\mathrm{NET}} = \dot{W}_{\mathrm{COMP}} - \dot{W}_{\mathrm{EXP}} = \dot{W}_{\mathrm{NET}}\left(T_{\mathrm{II}}, \Delta T_{\mathrm{cold}}, \Delta T_{\mathrm{warm}}\right)$$

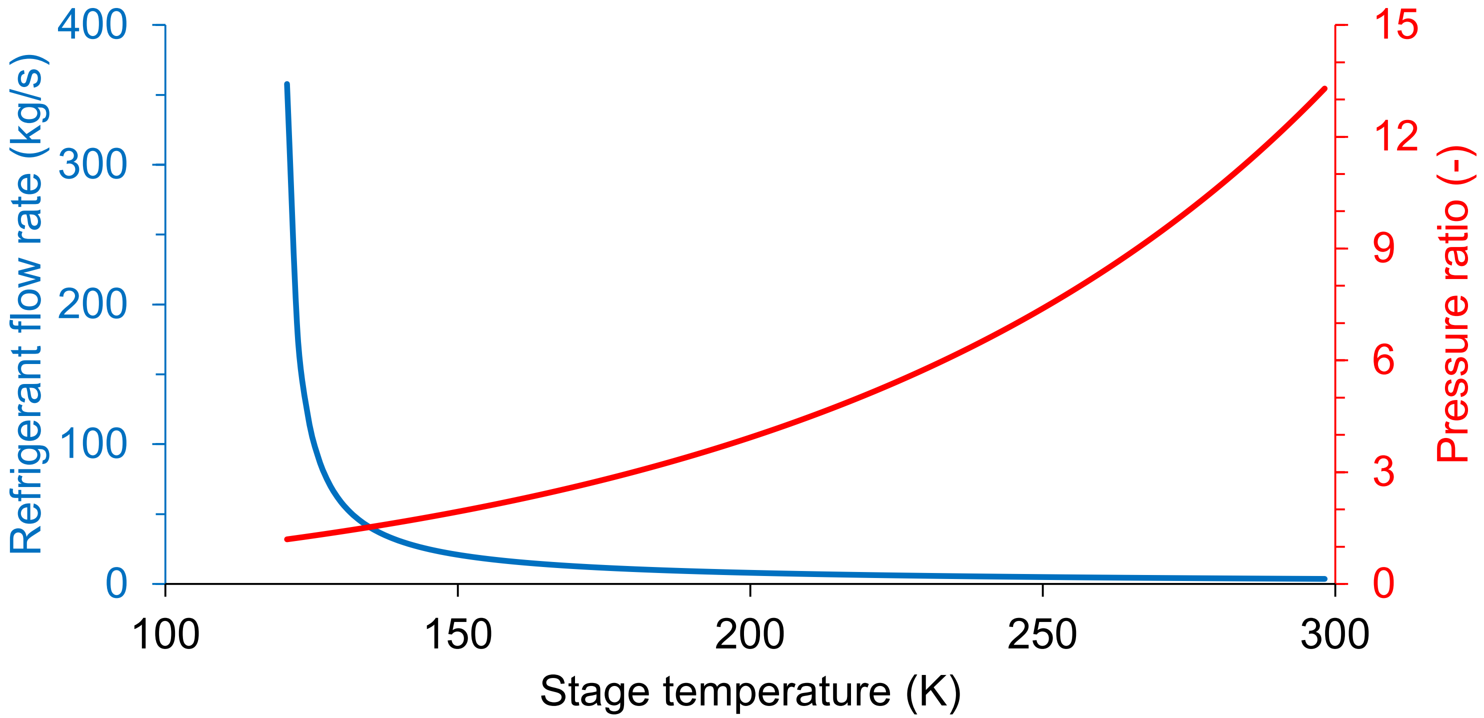
Simplified model

- Case study:
  - $(\dot{m}c_p)_{\mathrm{NG}} = 3.5$ kJ/K
  - $c_{p,\mathrm{R}} = 1$ kJ/kgK
  - $T_\mathrm{I} = 300$ K
  - $T_\mathrm{III} = 115$ K
  - $\eta_{s,\mathrm{COMP}} = \eta_{s,\mathrm{COMP}} = 0.8$
  - $\Delta T_\mathrm{cold} = 4$ K
  - $\Delta T_\mathrm{warm} = 8$K

- Studying the influence of the stage temperature T_II

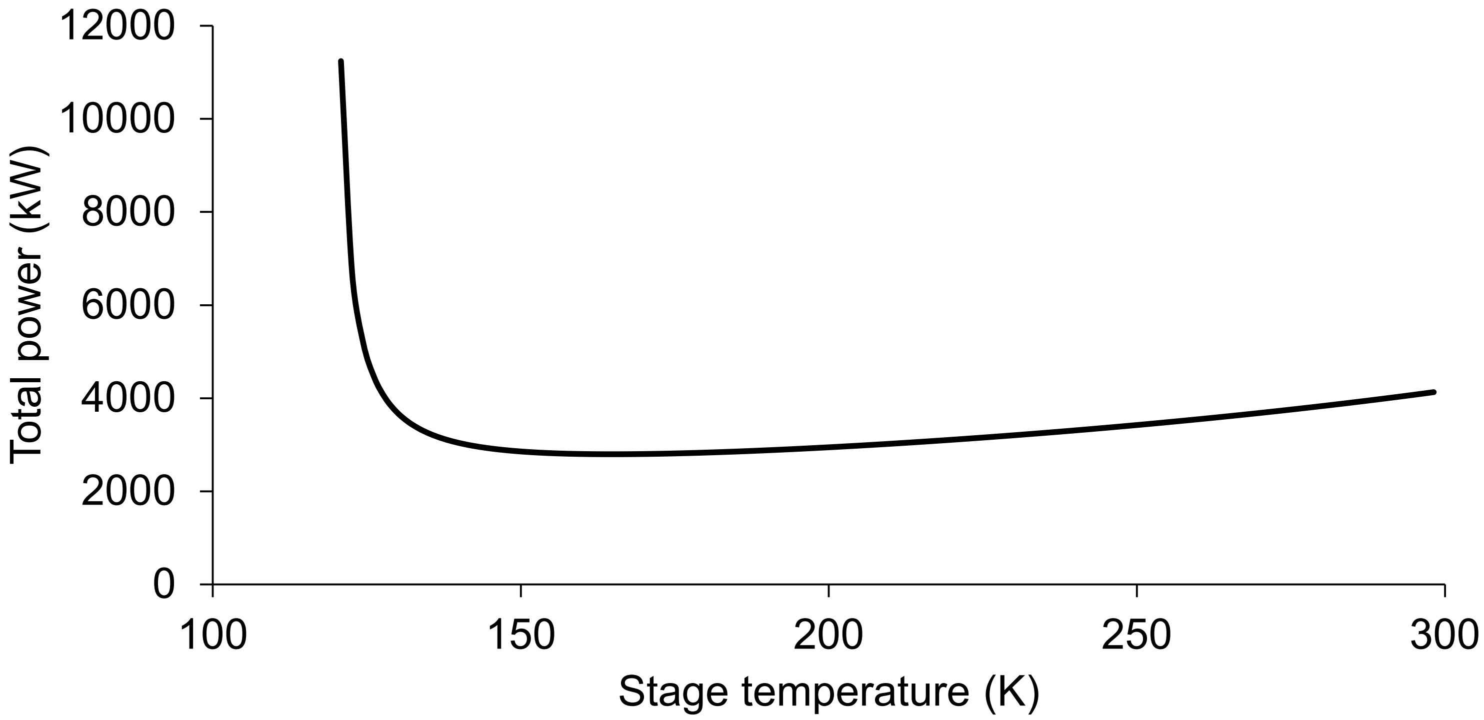
Simplified model

- Flow rate / pressure ratio



Simplified model

- Net power consumption:



Simplified model

- Optimal cold end temperature difference $\Delta T_{\text{cold}}{}^{*}$:
  - From thermodynamics:

$$\Delta T_{\text{cold}}^{*} = \Delta T_{\text{min}}$$

- Optimal warm end temperature difference $\Delta T_{\text{warm}}{}^{*}$:
  - Locating extrema (isentropic efficiency sufficiently high):

$$\frac{\mathrm{d}\dot{W}_{\text{NET}}}{\mathrm{d}\left(\Delta T_{\text{warm}}^{*}\right)} = 0$$

$$\Rightarrow \Delta T_{\text{warm}}^{*} = \Delta T_{\text{min}}$$

Simplified model

- Optimal stage temperature T_{II}^{*}:
  - Locating extrema:

$$\frac{\mathrm{d}\dot{W}_{\mathrm{NET}}}{\mathrm{d}T_{\mathrm{II}}^{*}} = 0$$

  - Optimal stage temperature T_{II}^{*} as a function of T_{I}, T_{III}, ΔT_{warm}, ΔT_{cold}, $\eta_{s,\mathrm{COMP}}$, $\eta_{s,\mathrm{EXP}}$

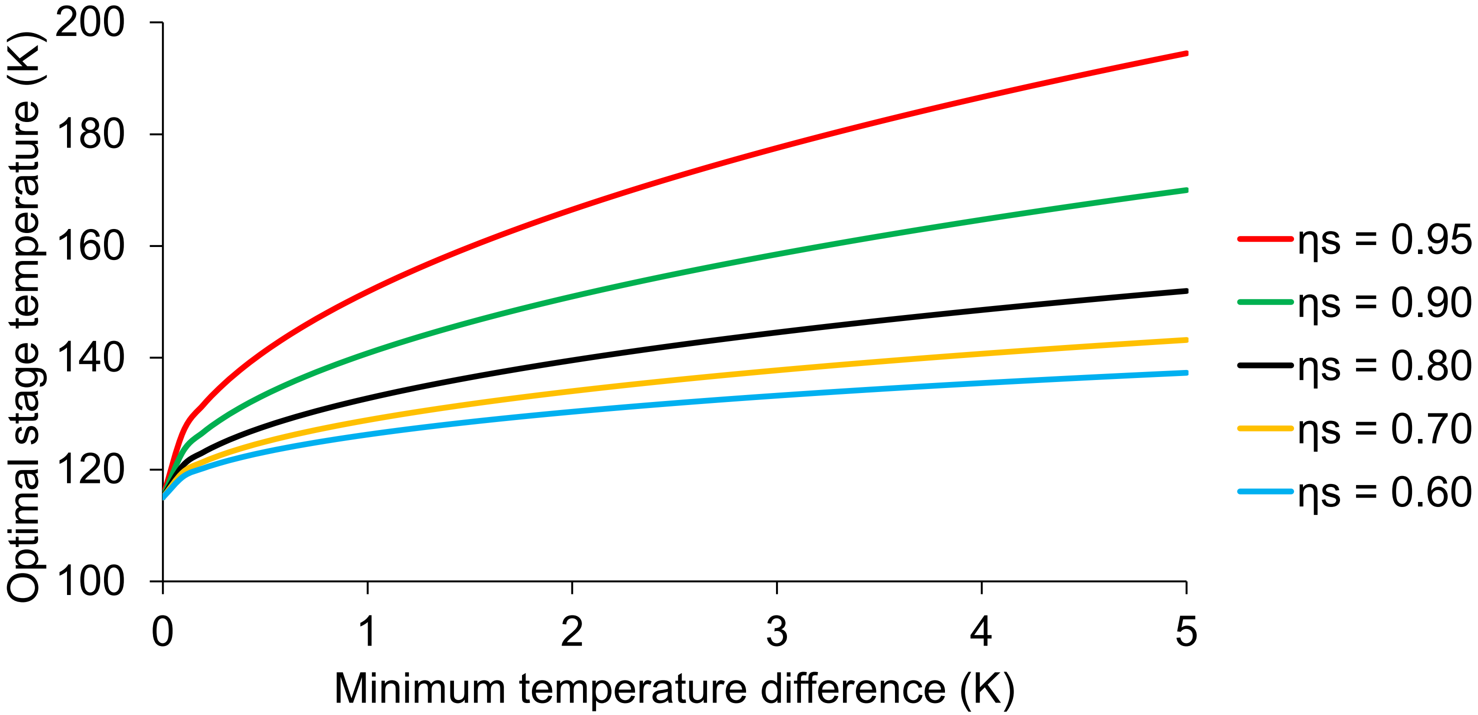
Simplified model

- LNG case study
  - $T_\mathrm{I} = T_3 = 293.15\ \mathrm{K}$
  - $T_\mathrm{III} = 115.00\ \mathrm{K}$
  - $\eta_{s,\mathrm{COMP}} = \eta_{\mathrm{s,COMP}} = \eta_\mathrm{s}$
  - $\Delta T_\mathrm{cold} = \Delta T_\mathrm{warm} = \Delta T_\mathrm{min}$

- Optimal stage temperature plotted for different values of η_s and ΔT_min

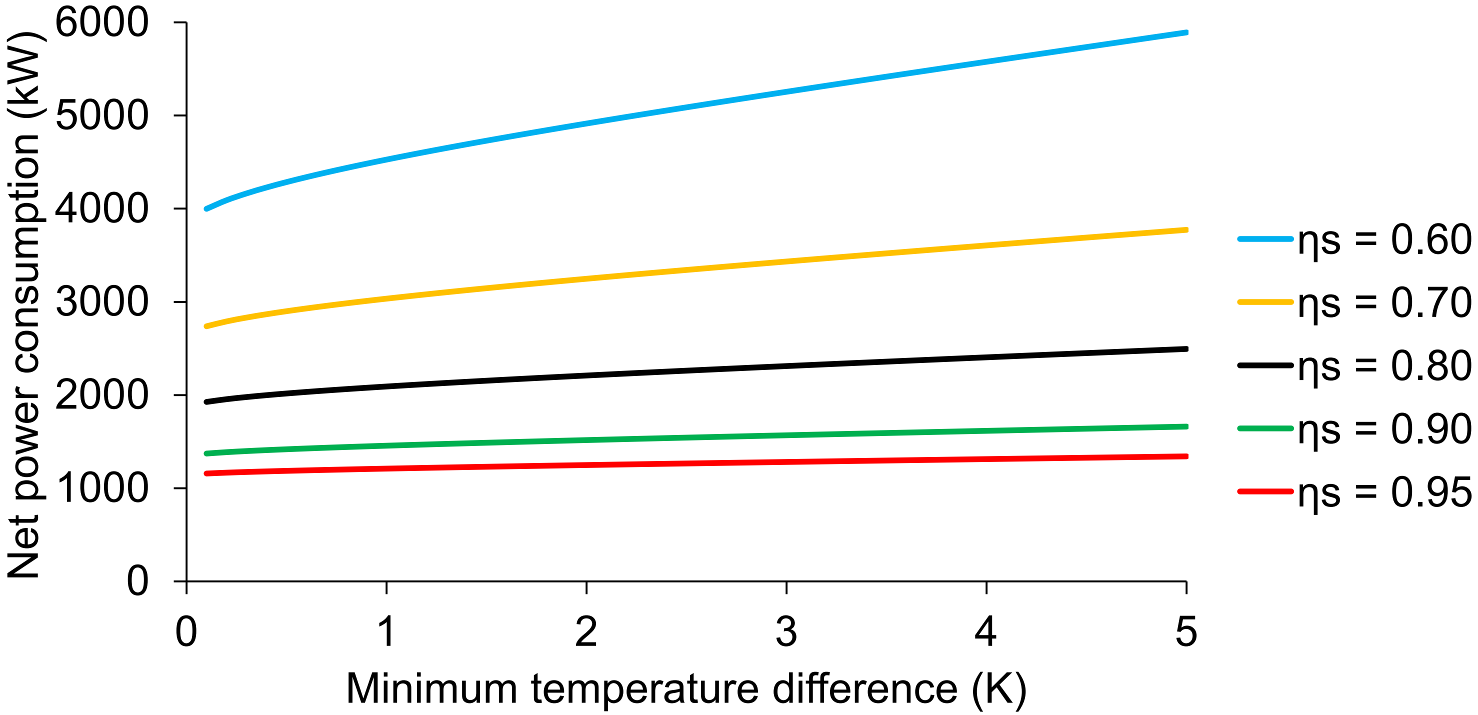
Simplified model

- Optimal stage temperature T_{II}^{*}:



Simplified model

- Net power consumption at T_{II}^*:



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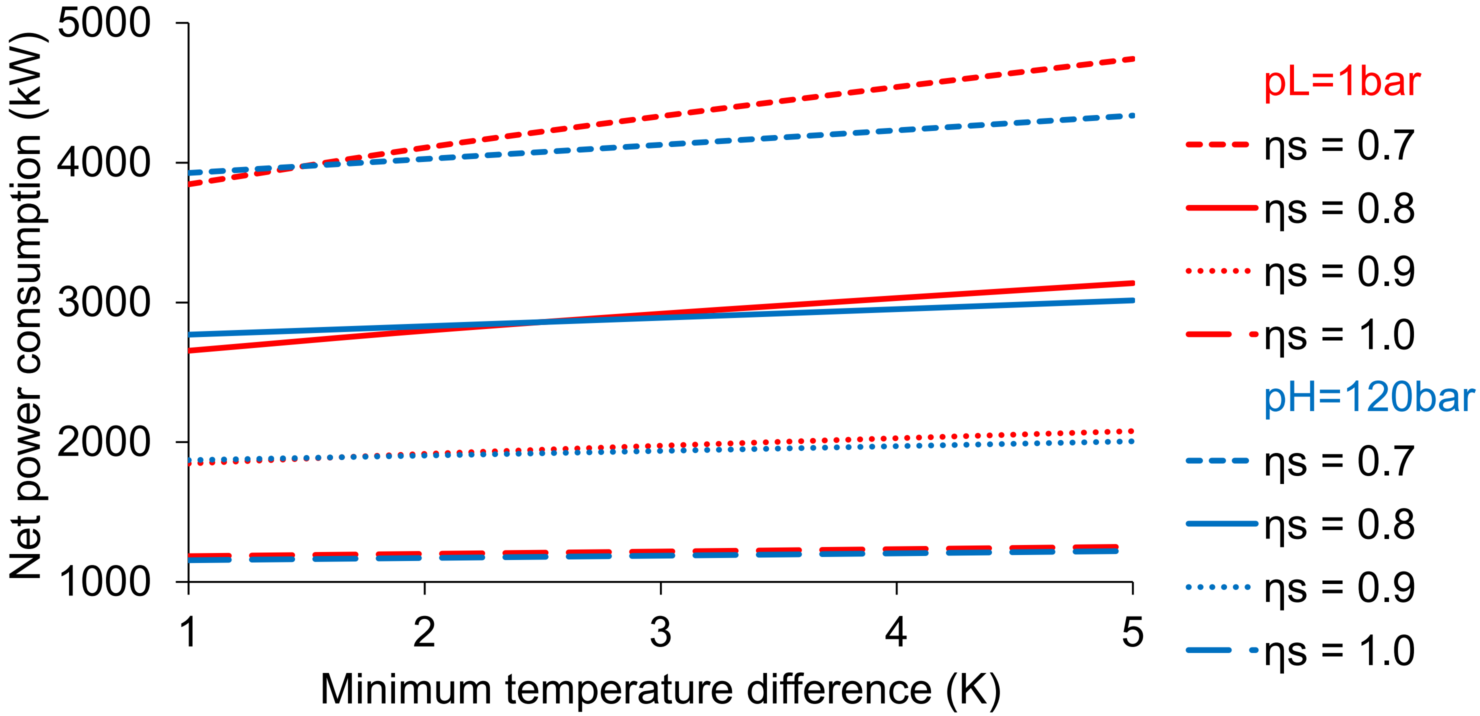
Rigorous model

- Decision variables:
  - Refrigerant flow rate $\dot{m}_R$
  - Stage temperature T_{II}
  - Pressure ratio p_H/p_L
  - Low pressure level p_L (Alternatively p_H)

  - Pressure levels: 1 bar ≤ p ≤ 120 bar

Rigorous model

- Optimization results:

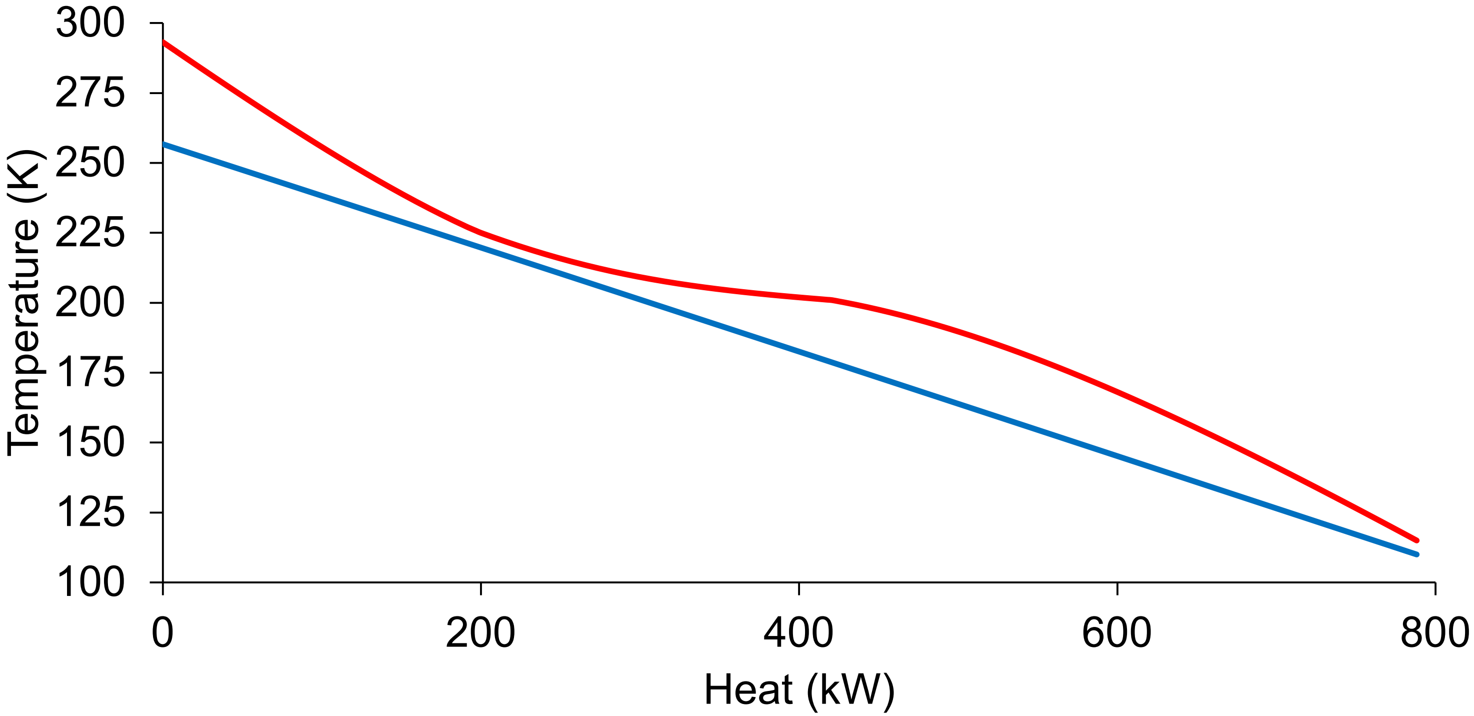


Rigorous model

ΔT_{min} (K)	η_s (-)	$\dot{W}$ (kW)	T_{stage} (K)	$\dot{m}_R$ (kg/s)	p_L (bar)	p_H (bar)	p_H/p_L (-)	ΔT_{cold} (K)	ΔT_{warm} (K)
1.0	0.70	3845.5	130.5	52.6	1	1.92	1.92	1.0	1.0
1.0	0.80	2654.6	135.0	40.2	1	2.05	2.05	1.0	1.0
1.0	0.90	1847.6	146.1	25.7	1	2.55	2.55	1.0	1.0
1.0	1.00	1155.5	293.2	5.0	5.31	120	22.60	1.0	31.5
3.0	0.70	4127.9	197.5	12.1	12.98	120	9.25	3.0	3.0
3.0	0.80	2890.2	213.9	9.0	10.28	120	11.68	3.0	3.0
3.0	0.90	1937.7	249.7	5.9	6.44	120	18.63	3.0	3.0
3.0	1.00	1188.0	293.2	5.1	5.01	120	23.93	3.0	33.5
5.0	0.70	4337.2	198.6	12.0	11.73	120	10.23	5.0	5.0
5.0	0.80	3014.6	215.1	8.9	9.30	120	12.90	5.0	5.0
5.0	0.90	2006.3	251.7	5.8	5.79	120	20.73	5.0	5.0
5.0	1.00	1221.5	293.2	5.1	4.73	120	25.37	5.0	35.5

Rigorous model

- Composite curves (ΔT_{min} = 5 K, η_s = 1.0):



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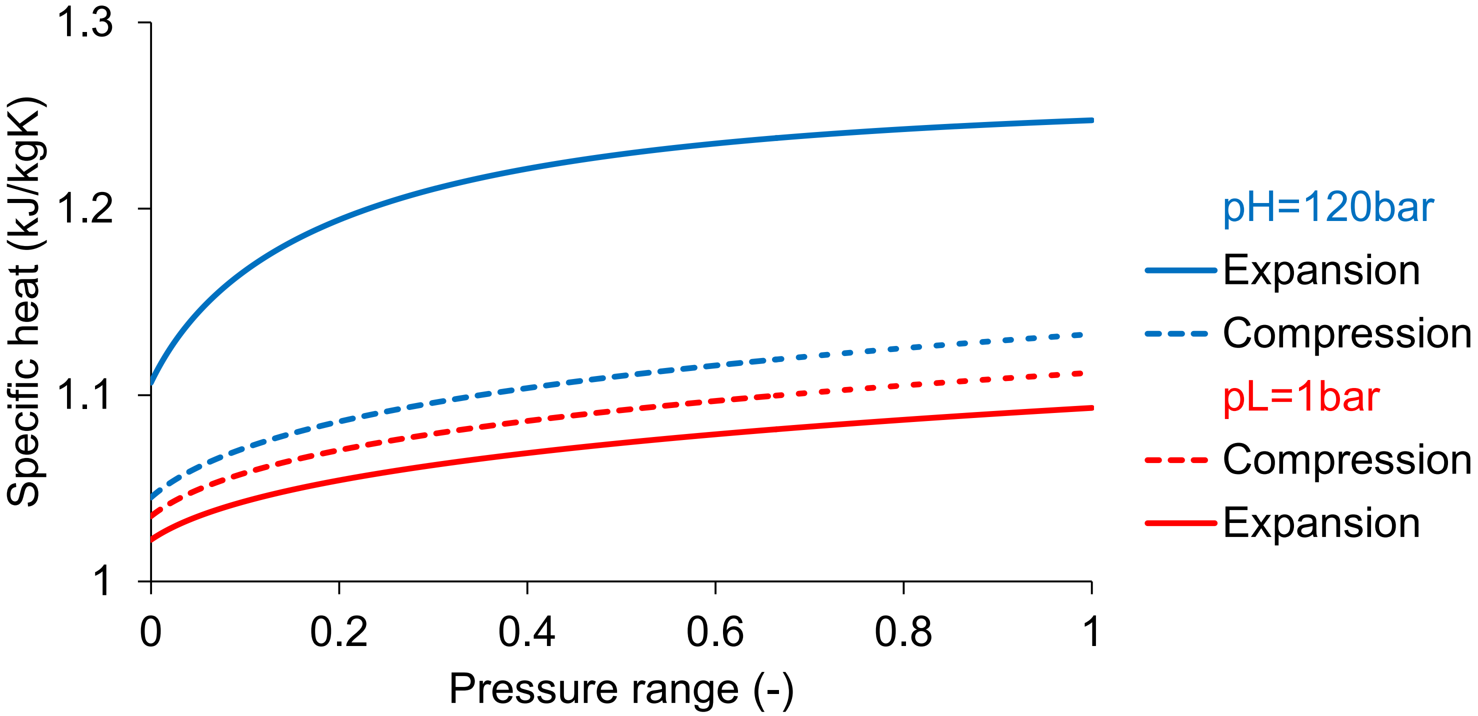
Comparison

		Simplified		Rigorous (p_L = 1 bar)		Rigorous (p_H = 120 bar)	
ΔT_{min} (K)	η_s (-)	T_{stage} (K)	$\dot{W}_{net}$ (kW)	T_{stage} (K)	$\dot{W}_{net}$ (kW)	T_{stage} (K)	$\dot{W}_{net}$ (kW)
1.0	0.70	128.9	3835.9	130.5	3845.5	196.3	3926.5
1.0	0.80	132.7	2644.1	135.0	2654.6	212.6	2769.7
1.0	0.90	140.8	1841.0	146.1	1847.6	247.6	1871.5
3.0	0.70	137.8	4339.8	141.0	4332.5	197.5	4127.9
3.0	0.80	144.5	2921.4	149.0	2919.1	213.9	2890.2
3.0	0.90	158.5	1982.4	169.3	1975.0	249.7	1937.7
5.0	0.70	143.2	4769.6	148.0	4742.7	198.6	4337.2
5.0	0.80	152.0	3153.6	158.5	3138.2	215.1	3014.6
5.0	0.90	170.0	2100.2	185.9	2079.3	251.7	2006.3

Comparison

- Specific heat compression/expansion:



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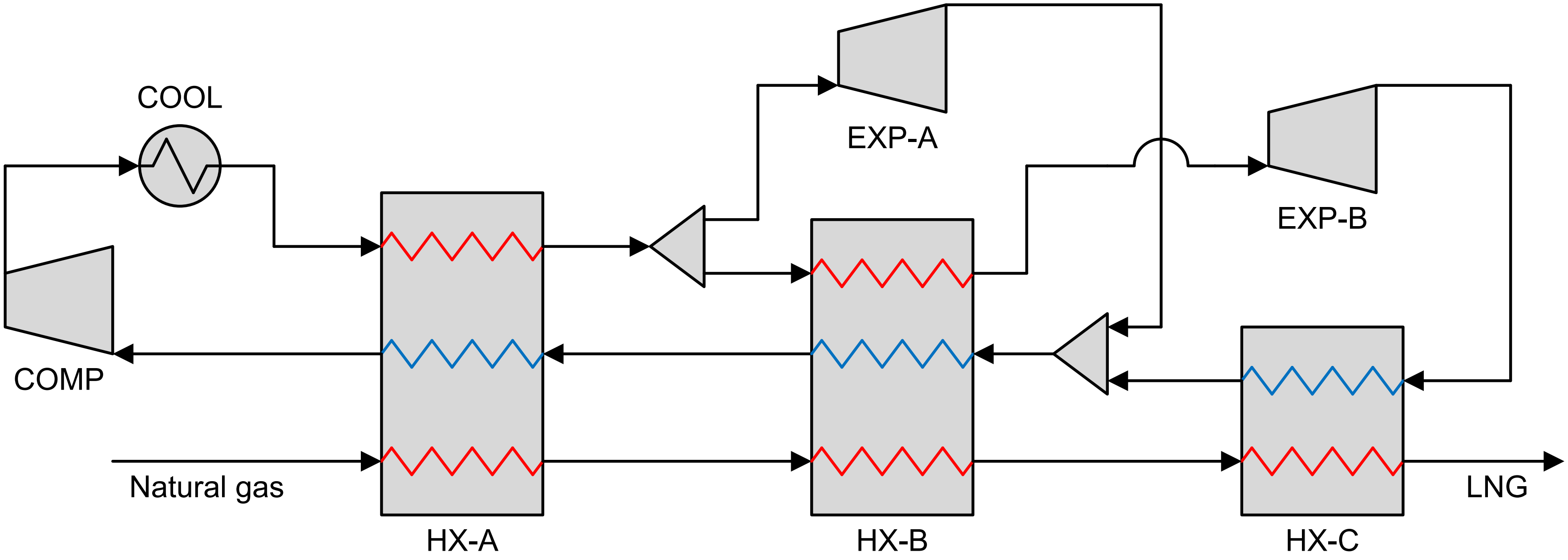
Conclusions

- Single expander process optimized for different values of ΔT_{min} and η_s for both simplified and rigorous thermodynamic model
- Two local optimal solutions observed for the rigorous model, of which one is close to the solution of the simplified model
- For most cases, the best solution found is significantly different for the two models

Future work

- Extensions to dual expander process



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