Karlsruhe Institute of Technology

Institute for Beam Physics and Technology
Institute for Technical Thermodynamics and Refrigeration

Model development and optimization of cryogenic mixed-refrigerant cycles with phase separators

J. Reichert[1*], F. Boehm[2], S. Grohmann[1,2]

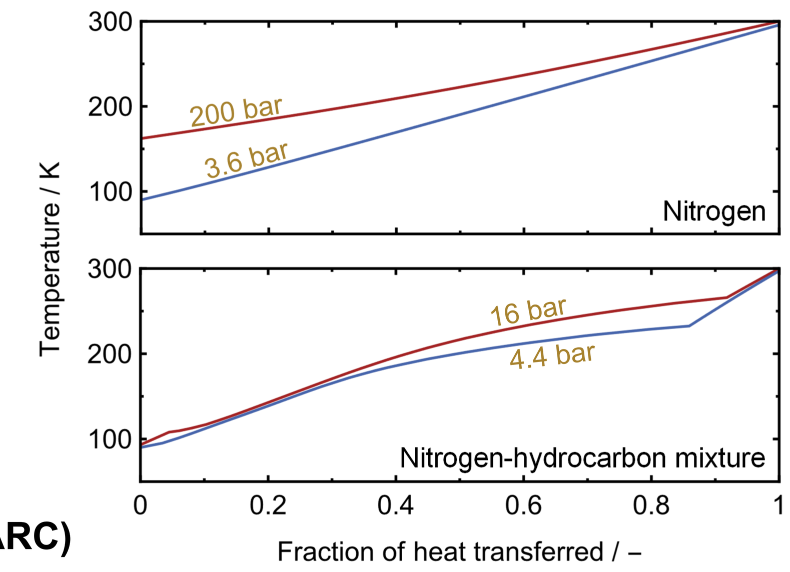
[1]Institute for Beam Physics and Technology, Herrmann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[2]Institute for Technical Thermodynamics and Refrigeration, Engler-Bunte-Ring 21, 76131 Karlsruhe, Germany
*jakob.reichert@kit.edu

CEC/ICMC 2025, Reno, US, May 18-22, 2025

Motivation

- Efficient cooling at low temperatures
  - ULT-freezers, $T_0 \leq 200$ K
  - HTS cooling, $T_0 \leq 80$ K
- Wide-boiling refrigerant mixtures
- Freezing of high-boiling components limits efficiency at low temperatures
  - CMRC cascade
  - **Auto-cascade refrigeration cycle (ARC)**

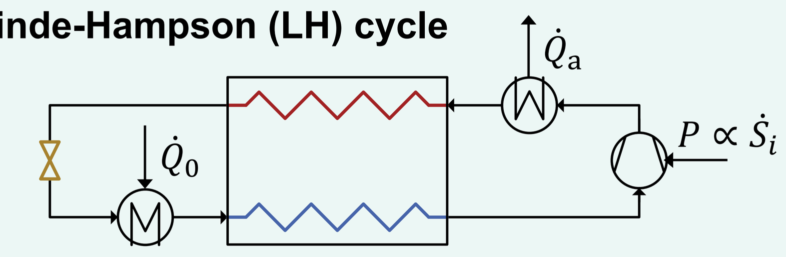
Temperature profiles of internal HX



Linde-Hampson (LH) cycle

$$ds = \frac{T_{hot} - T_{cold}}{T_{hot} T_{cold}} dq$$

$$ds = -\frac{v}{T} dp$$



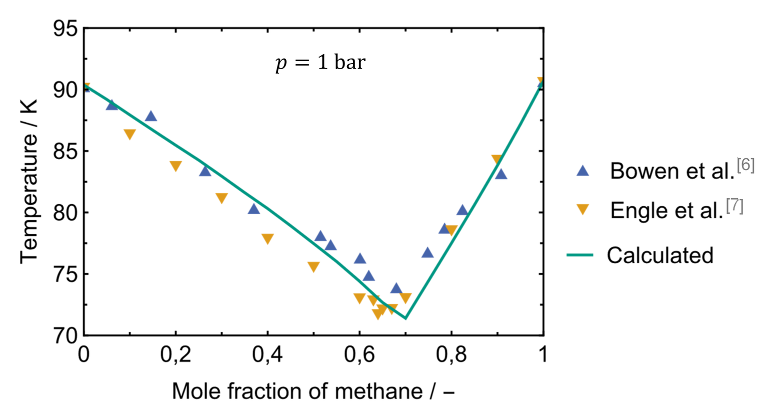
Properties of refrigerant mixtures

[4]

- Cubic equations of state
  - Peng-Robinson[1]
  - α-function by Twu et al.[2,3]
- Open source tool CoolProp[4]

- **Freezing point estimation**
  - Solid-liquid-equilibrium: $f_i^L = f_i^S$
  - Assume pure solid: $f_i^S = f_{0i}^S$
  - Calculation of f_{0i}^S with f_{0i}^L according to Prausnitz et al.[5]

Example: Methane-ethane-SLE

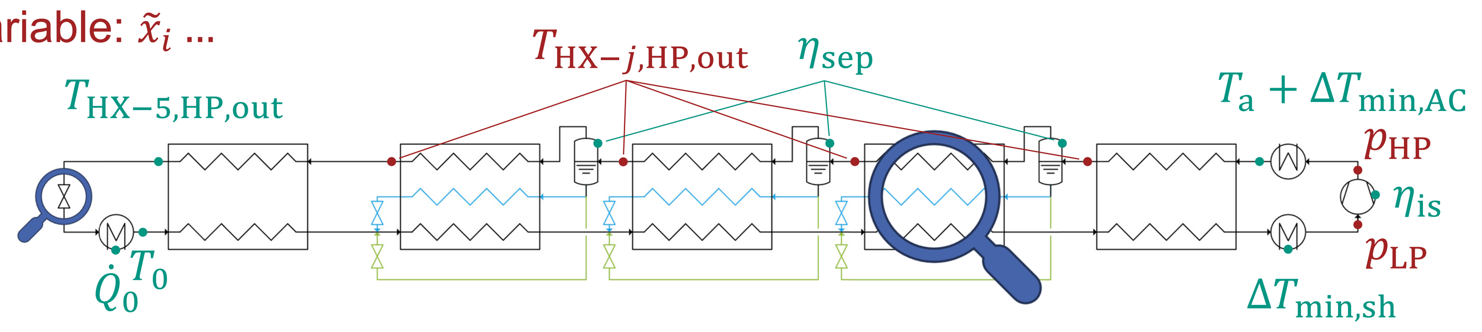


$$\ln\left(\frac{f^L}{f^S}\right) = \frac{\Delta \bar{h}^{SL}}{R T_{tr}}\left(\frac{T_{tr}}{T} - 1\right) + \frac{\Delta \bar{c}_p^{SL}}{R}\left(\ln\left(\frac{T_{tr}}{T}\right) - \frac{T_{tr}}{T} + 1\right) + \frac{\Delta \bar{v}^{SL}}{R T_{tr}}(p - p_{tr})$$

Process modeling

Constant: Δp_k, $\Delta T_{min,HX}$ ...
Variable: $\tilde{x}_i$ ...

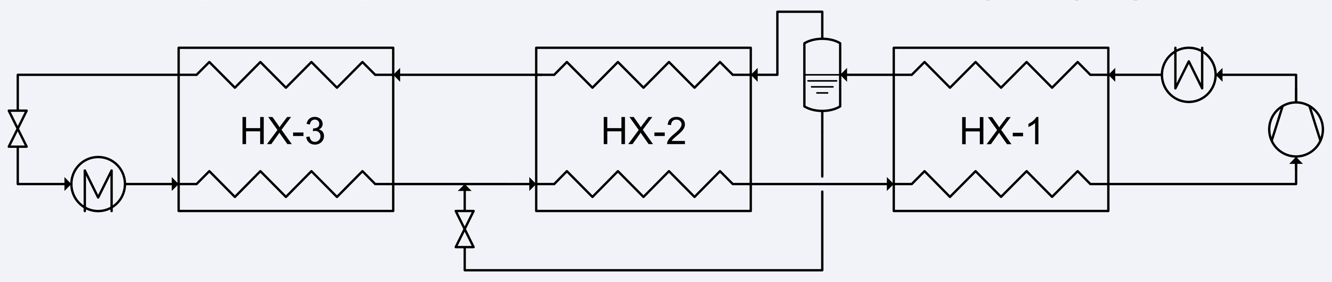
- Model built in Wolfram Mathematica[8]



General assumptions:
- Steady state
- Adiabatic components and pipes
- Constant pressure losses

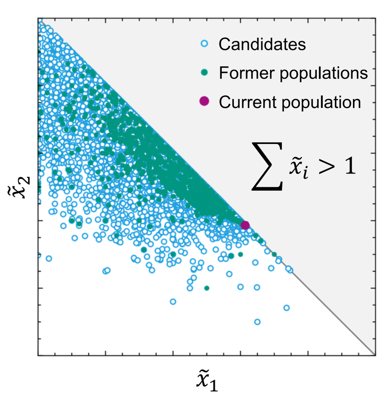
- Objective: Calculation of power demand
- Consistency checks
  - Temperature profiles
  - Freezing point estimation

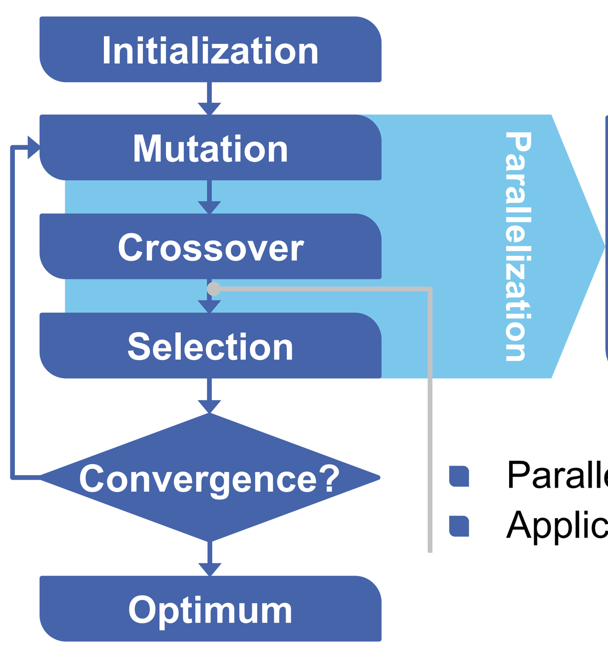
ARC-13 with 1 phase separator and 3 internal heat exchangers (HX)



Optimization

Differential Evolution[9,10]
- Evolutionary algorithm
- No derivatives required
- Global optimization[11]

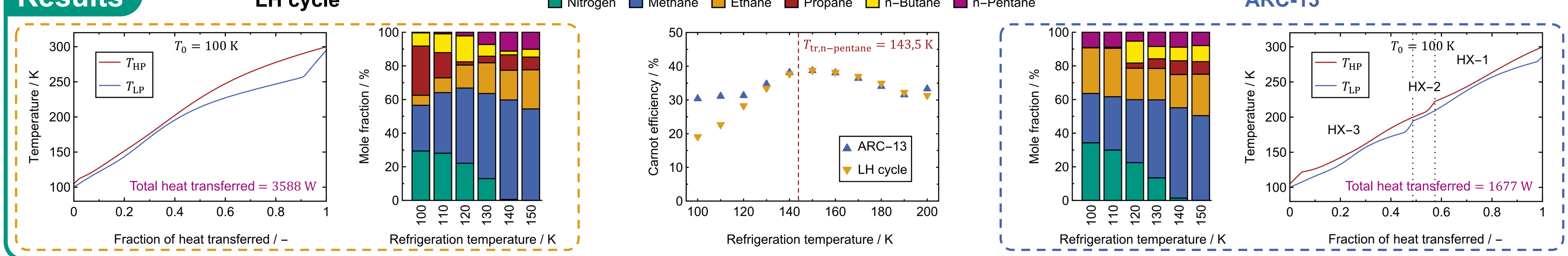




bw|HPC [12]

- Parallel process simulation
- Application of penalty functions

Results



[1] D. Peng and D. Robinson, "New Two-Constant Equation of State," Ind. Eng. Chem. Fundam., vol. 15, 1976.
[2] C. H. Twu, D. Bluck, J. R. Cunningham, and J. E. Coon, "A cubic equation of state with a new alpha function and a new mixing rule," Fluid Ph. Equilib., vol. 69, 1991.
[3] I. H. Bell, M. Satyro, and E. W. Lemmon, "Consistent Twu Parameters for More than 2500 Pure Fluids from Critically Evaluated Experimental Data," J. Chem. Eng. Data, vol. 63, no. 7, 2018.
[4] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," Ind. Eng. Chem. Res., vol. 53, no. 6, 2014.
[5] J. M. Prausnitz, R. N. Lichtenthaler, and E. G. de Azevedo, Molecular thermodynamics of fluid-phase equilibria, 2nd ed. in Prentice Hall international series in the physical and chemical engineering sciences. Englewoods (N. J.): Prentice Hall, 1986.
[6] L. Bowen et al., "Experimental measurement and model prediction of solid-liquid equilibrium for methane-ethane binary system," J. Chem. Thermodyn., vol. 172, 2022.
[7] A. E. Engle et al., "Phase Diagram for the Methane–Ethane System and Its Implications for Titan's Lakes," Planet. Sci. J., vol. 2, no. 3, p. 118, 2021.
[8] Wolfram Research Inc., Mathematica, Version 13.3, Champaign, IL, 2023.
[9] R. Storn and K. Price, "Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces," J. Glob. Optim., vol. 11, no. 4, 1997.
[10] K. V. Price, R. Storn, J. A. Lampinen, and R. Storn, Differential evolution: a practical approach to global optimization. In Natural computing series. Berlin Heidelberg: Springer, 2005.
[11] F. Boehm and S. Grohmann, "Modelling and optimization of cryogenic mixed-refrigerant cycles for the cooling of superconducting power cables," IOP Conf. Ser.: Mater. Sci. Eng., vol. 1301, no. 1, 2024.
[12] bwHPC, bwUniCluster 2.0. URL: https://wiki.bwhpc.de/e/BwUniCluster2.0 (last checked: 05.05.2025)