Modelling and optimization of cryogenic mixed-refrigerant cycles for the cooling of superconducting power cables

F Boehm, S Grohmann, *Cryogenic Engineering Conference, Honolulu, C1Or2A-01, July 10, 2023*
SuperLink – 15 km superconduction in Munich

- Progressing electrification due to energy transition
- Upgrading power grid is imperative (age, performance)

- Lower space demand
- No electromagnetic emissions
- No joule heating
- Higher transmission performance

[1] www.nkt.de

SuperLink – Cooling stations

- Cooling temperature below 77 K
- 15-30 kW per cooling station
- Low-maintenance & reliable
- Low space requirement
- Low energy demand


[4] stirlingcryogenics.eu

CMRC cascade

- Single-stage CMRC inefficient for very low temperatures (70 K)
- Model presentation of cascade in future publication

This presentation:
- Modelling single-stage CMRC
- Optimization concept
Implementation

[6]: Wolfram Research
[7]: CoolProp

\begin{align*}
\text{Temperature} / \text{K} & \quad \text{Transferred heat} / - \\
\end{align*}
Process Simulation

- Single-stage CMRC (Linde-Hampson)
- Model built in Wolfram Mathematica
- Steady-state simulation
  - Single-stage compressor, fixed efficiency
  - High and low pressures, pressure drop
  - Temperature levels, minimum temperature approach
  - Mixture components and concentrations

Results
- Energy demand
- Temperature profile
Pinch Point Detection

- Finding pinch points through generated temperature profiles
- Quantifying „physicality“ with equation developed by Kochenburger [8]

\[ A = \int_0^{\hat{Q}_{\text{total,HP}}} \max\{0, \Delta T_{\text{min,HX}} - (T_{\text{HP}} - T_{\text{LP}})\} \, d\hat{Q}_{\text{HP}} \]

- Needed for penalty functions in optimization
Optimization

- Concentrations
- Pressures
- Temperatures

CMRC circuit
Complex correlations
No derivatives available
→ disqualifies many algorithms

- Energy demand
- Pinch point analysis
Optimization

- No derivatives needed
- Independent of starting values
  - Global optimization
- Treatment of boundary conditions
- Abort criterion definable

Differential Evolution\(^{[9,10]}\)
- Genetic algorithm
- Global optimization
  „Exploration & Exploitation“
Optimization

- Population based approach
  - lower chances of local optima

- Runs in “generations”
  - Mutation, Recombination & Selection

- Optimization parameters:
  - Population size
  - Scale factor/differential weight
  - Crossover probability
  - Applying boundary conditions
  - Penalty functions
  - Abort criterion
Parallelization & Cluster Computing

- Differential Evolution lends itself to parallelization
  - Different candidates in the same generation can be calculated independently

- HPC cluster (bwUniCluster 2.0) available @KIT
First results

- Composition optimization for $T_{\text{cooler,in}} = 90 - 150$ K
- Constant pressures
  - $p_{\text{HP}} = 16$ bar
  - $p_{\text{LP}} = 4$ bar
  - $\Delta T_{\text{min,HX}} = 2$ K

![Graph showing optimum mixture composition vs. cooler inlet temperature]

- Methane
- Ethane
- Propane
- Nitrogen
Conclusions and outlook

- Process simulation
  - More advanced single- and multi-stage compressor model
  - CMRC (auto-)cascades

- Optimization
  - Parameters
  - Penalty functions
  - Algorithm modifications
Bibliography


Thank you for your attention!