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Optimization Potential for Cooling Superconducting Power Cables by Using Cryogenic Mixed Refrigerant Cycles

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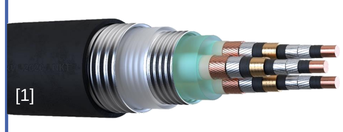
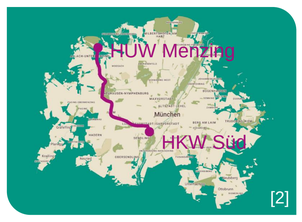
Motivation

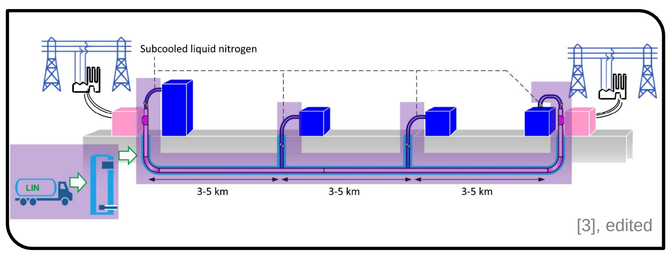

[1]

- progressing electrification due to energy transition
  → Increasing energy demand
- upgrading power grid is imperative
- transmission performance and age of current cables

- 110 kV connection of main transformer station (HUW) Menzing and thermal power plant (HKW) Süd
- 500 MVA in the compact cable – will be the longest HTS cable
- lower space demand and higher transmission performance
- no electromagnetic emissions and no joule heating



[2]



[3], edited

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SuperLink

Superconducting Applications

Cooling Technologies

bwUniCluster 2.0

Process Modelling

Parallelization

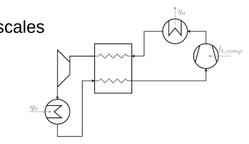
Differential Evolution

Technologies for providing low temperatures

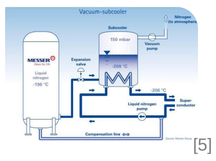
Stirling cooler
- medium efficiency
- low cooling power
  - number of coolers
  - economic efficiency
- high-maintenance


[4]

Reverse-Brayton-Cooler
- highly efficient in commercial scales
- broad operational experience
- complex design
- limited scalability of expander in cold section

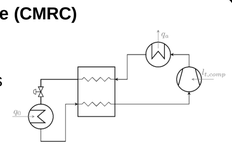


Nitrogen subcooler
- low technical complexity
- operational experience AmpaCity[5]
- continuous nitrogen demand

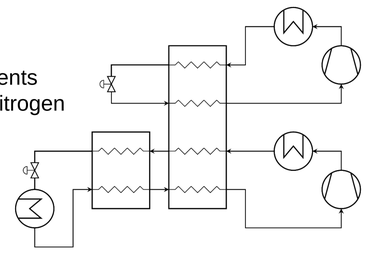


[5]

Cryogenic mixed refrigerant cycle (CMRC)
- low pressures
- matching heat capacity flows
  → small temperature differences
- simple architecture:
  no moving parts in cold section
- scalable and adaptable



CMRC cascades
- temperatures below 70 K
- no freezing out of high boiling components
- 1st cycle: methane, ethane, propane, nitrogen
- 2nd cycle: nitrogen, oxygen, neon

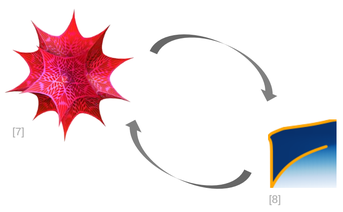


Finding the optimum conditions
- components
- concentrations
- pressures
- temperatures
- …

→ **Large number of parameters**

Modelling

- process simulation in Mathematica
  → more control through self-written process simulation
- thermodynamic property data through open-source software CoolProp[6]
  - Peng-Robinson Equation of State

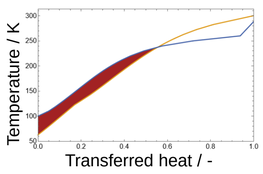

[7] [8]

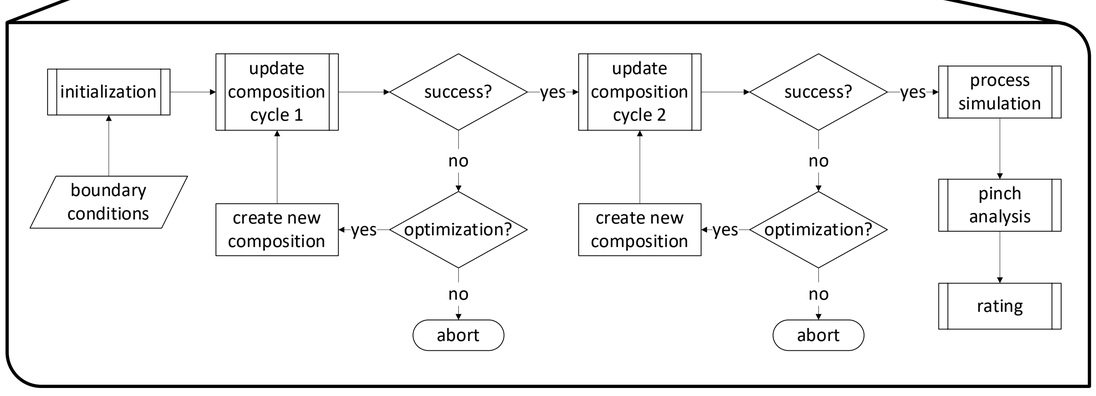
- extension of existing wrapper (C++ to Mathematica)
- lots of external code necessary to ensure reliability of property data
  - liquid-liquid equilibrium at low vapor fractions
  - multi-phase equilibria not available in CoolProp or commercial software

- concentrations
- pressures
- temperatures

CMRC cascade
complex correlations
no derivatives available
→ disqualifies many optimization algorithms

- energy demand
- pinch point analysis





Optimization

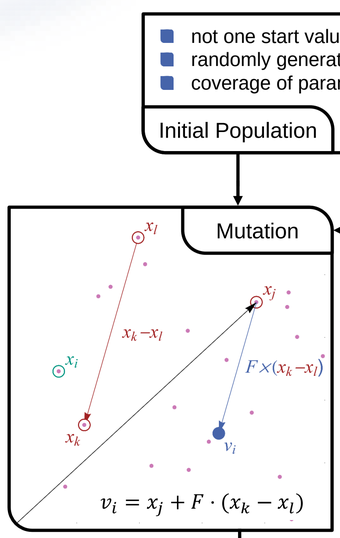
- no derivatives needed
- independent of starting values
- global optimization
- treatment of boundary conditions
- abort criterion definable

Differential Evolution[9,10]

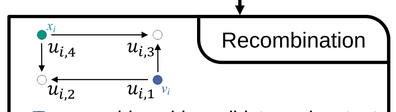
- genetic algorithm
- global optimization
  → „Exploration & Exploitation“
- enables parallel computation

- not one start value, population of candidates
- randomly generated or grid pattern
- coverage of parameter range

Initial Population → Mutation → Recombination → Selection → Abort criterion → Global Optimum



repeat for each candidate of the population



- recombine old candidate and mutant
- randomly decide for each trait

$P(u_{i,1})$	$P(u_{i,2}) = P(u_{i,3})$	$P(u_{i,4})$
cr^2	$cr \cdot (1-cr)$	$(1-cr)^2$

cr: Crossover probability

u_i

Process simulation → $f(u_i^*)$ → **Penalty functions**
Physically correct results (ΔT<0)
Substance data convergence

u_i^* → $g(u_i^*)$

Check boundary conditions → $g(x_i)$ → **Comparison** → x_i^*

[1] https://www.nkt.de/presse-events/nkt-entwickelt-den-prototyp-fuer-das-weltweit-laengste-supraleitende-stromkabel, last checked: 24 October 2022,
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[3] A. Alekseev, S. Grohmann and L. Decker, „Anforderungen an das Kühlsystem für lange HTSL-Leistungskabel“, german, 2020. DKV Tagung 2020 online, A I.11, 19-20 November 2020
[4] https://www.aim-ir.com/de/anwendungen-produkte/industrie/kryokuehler/mcc020.html, last checked: 24 October 2022
[5] F. Herzog, T. Kutz, M. Stemmle and T. Kugel, „Cooling unit for the AmpaCity project – One year successful operation“, Cryogenics, 80.2, p. 204-209, 2016. doi: 10.1016/j.cryogenics.2016.04.001
[6] I.H. Bell, J. Worrit, S. Quoilin and V. Lemort, “Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp”, Industrial & Engineering Chemistry Research 53.6, p.2498-2508, 2014. doi: 10.1021/ie4033999
[7] Wolfram Research (2021): https://content.wolfram.com/uploads/sites/10/2021/12/mathematica-13-spikey.png, last checked: 14 March 2023
[8] http://www.coolprop.org/_static/CoolPropLogo.png, last checked: 14 March 2023
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[10] K. Price, R. Storn and J. Lampinen, „Differential evolution - A practical approach to global optimization ; with 48 tables “, Springer Berlin, Heidelberg. ISBN: 978-3-540-20950-8. 2005.