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HTS cooling below 63 K with two-stage mixed-refrigerant cascades using low-flammability mixtures

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Motivation

Efficient and economic cooling of high-temperature superconductor (HTS) applications at temperatures below 63 K in the mid-scale capacity range (e.g. HTS cables, transformers, generators) using cryogenic mixed-refrigerant cascades (CMRC)

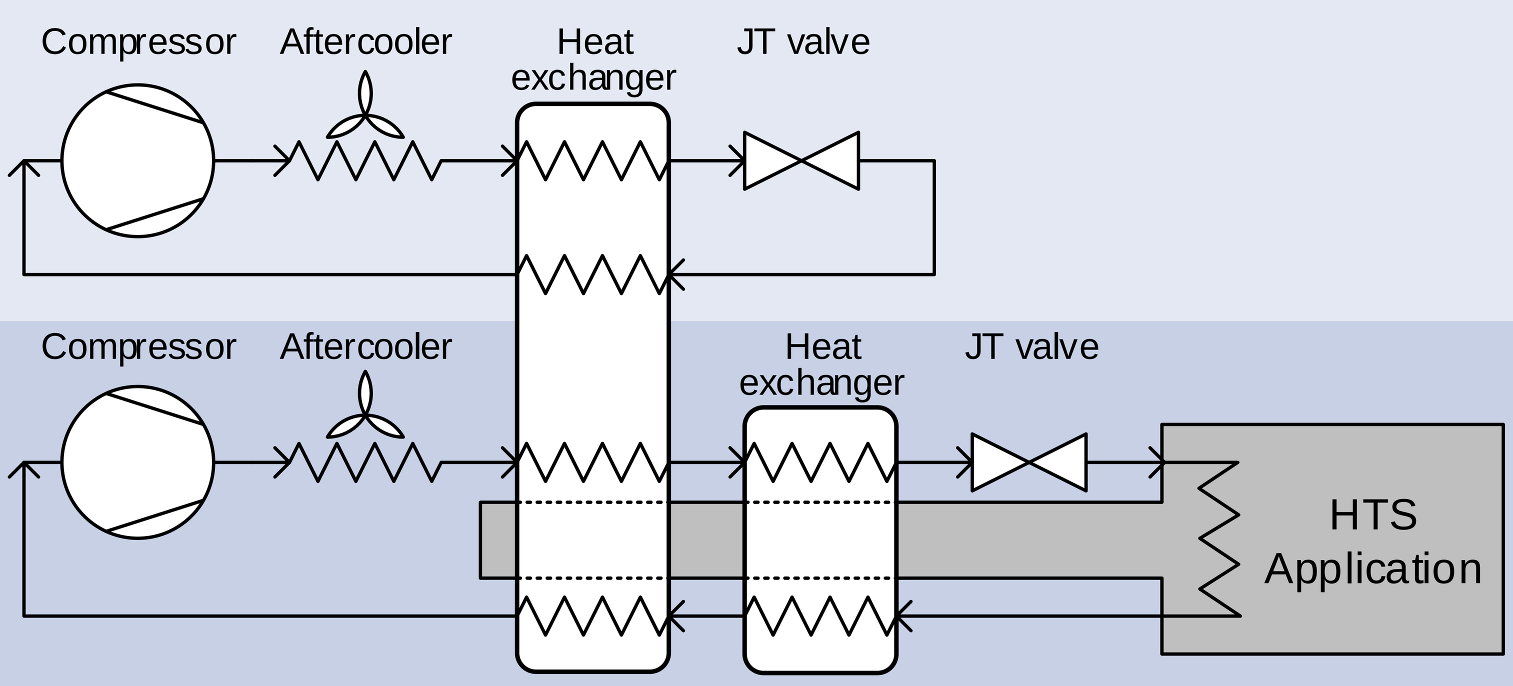
Potential

- Cooling temperature down to 50 K through oxygen-containing mixture at high pressure in second stage
  ➔ About 5 times higher HTS critical current densities compared to liquid nitrogen cooling at 77 K
- Low investment and operating cost (high efficiency)
- Closed cycle system, low maintenance
- Scalability from watt to megawatt range of cooling capacity

Focus of development

- Refrigerant mixture in pre-cooling stage must be compatible to electrical applications and oxygen-containing second stage mixtures
  ➔ Hydrocarbons should be avoided
- Heat exchanger design
- High-pressure operation
- Application for direct cooling of HTS current leads and for pre-cooling in hydrogen liquefaction

First stage (pre-cooling)



- Pre-cooling to 120 K
- Classical mixed-refrigerant cycle
- Moderate pressures (20 / 5 bar)

Second stage

- Operation down to 50 K
- Neon/nitrogen/oxygen mixture
- High pressures (100 / 40 bar) increase efficiency

New refrigerant mixture with low flammability in pre-cooling stage

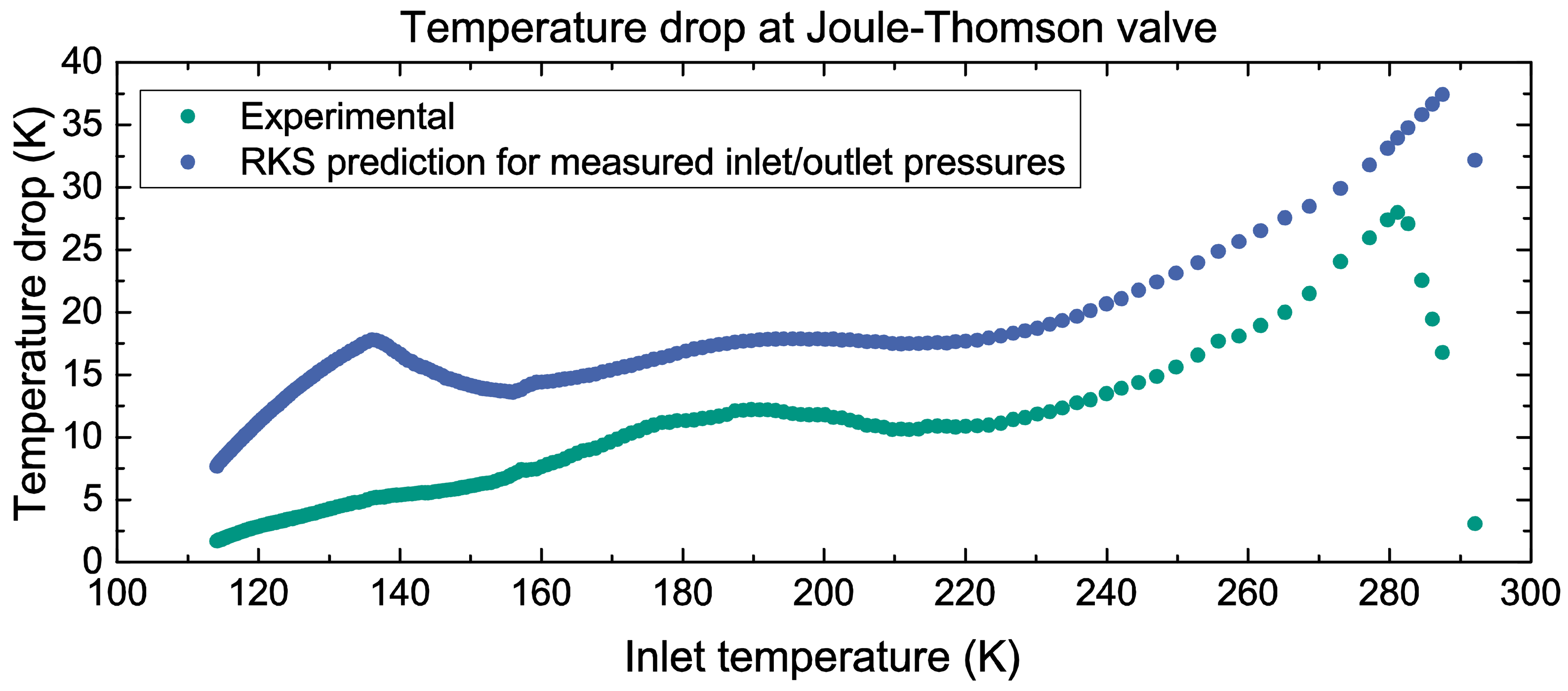
Mixture composition (optimized with Aspen Plus® model)

Refrigerant	Normal boiling temp. (K)	Triple point temp. (K)	Mole fraction
Nitrogen	77.4	63.2	15
Argon	87.3	83.8	17
R-14	145.1	89.5	21
R-23	191.1	118.0	5
R-1234yf	243.7	122.8	42

- R-1234yf only mildly flammable (ASHRAE class A2L)
- Other components non-flammable

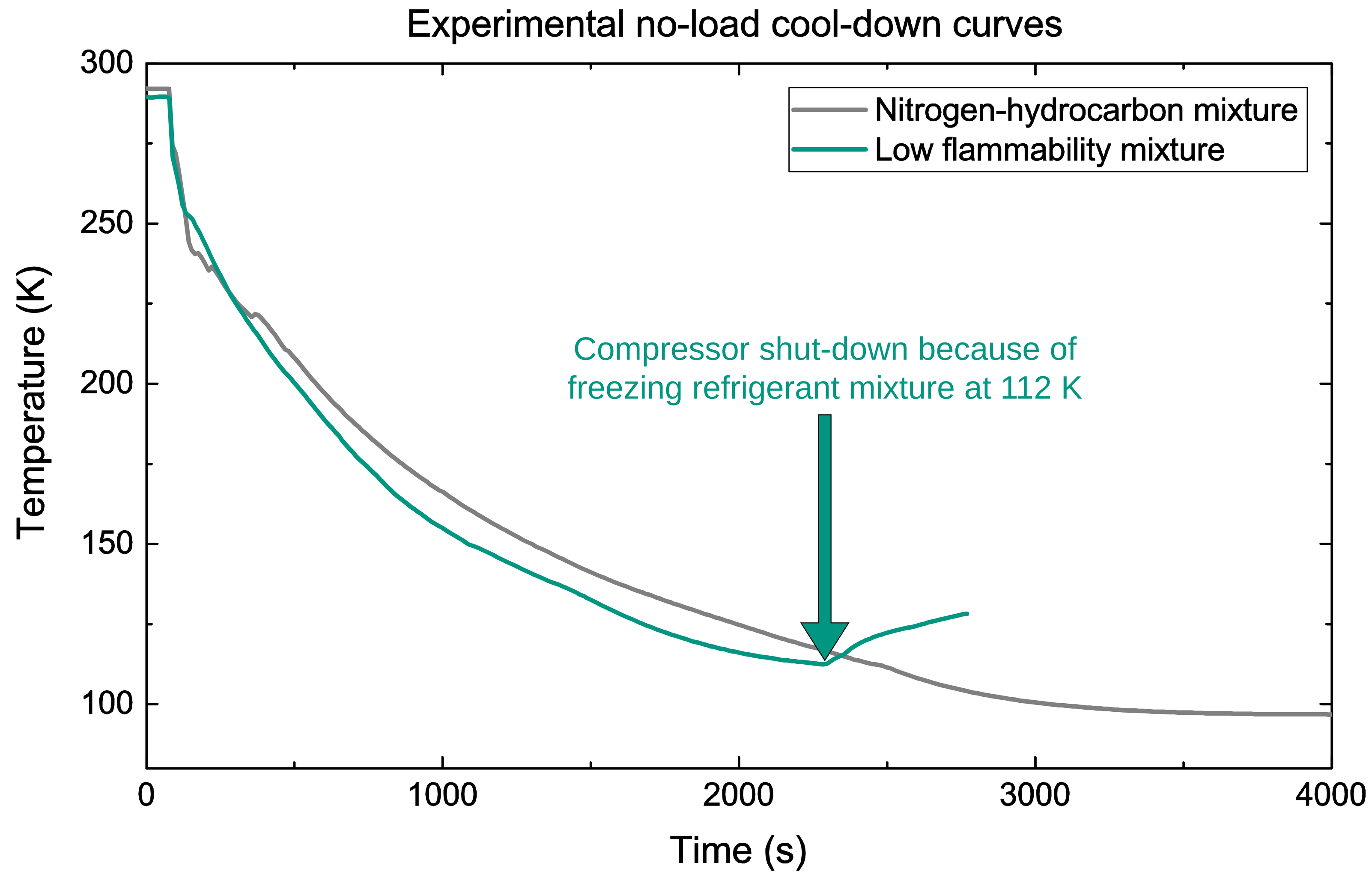
Thermodynamic modeling

- Redlich-Kwong-Soave (RKS) equation of state in Aspen Plus® (binary interaction parameters for R-1234yf with other components not available in literature)



Experimental performance results

- Test setup: single-stage mixed refrigerant cycle
- Cool-down curve of new refrigerant mixture compared to optimized nitrogen-hydrocarbon mixture (57 % propane, 14 % ethane, 17 % methane, 12 % nitrogen)



Conclusions and outlook

- Cooling performance comparable to nitrogen-hydrocarbon mixture
- Operation with sufficient margin above 112 K in order to avoid solidification
- Experimental phase equilibrium data required for improvement of thermodynamic modeling