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

New refrigerant mixture with low flammability in pre-cooling stage

Mixture composition (optimized with Aspen Plus® model)

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Normal boiling temp. (K)</th>
<th>Triple point temp. (K)</th>
<th>Mole fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>77.4</td>
<td>63.2</td>
<td>15</td>
</tr>
<tr>
<td>Argon</td>
<td>87.3</td>
<td>83.8</td>
<td>17</td>
</tr>
<tr>
<td>R-14</td>
<td>145.1</td>
<td>89.5</td>
<td>21</td>
</tr>
<tr>
<td>R-23</td>
<td>191.1</td>
<td>118.0</td>
<td>5</td>
</tr>
<tr>
<td>R-1234yf</td>
<td>243.7</td>
<td>122.8</td>
<td>42</td>
</tr>
</tbody>
</table>

- 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