Thermodynamic Comparison of Small Liquid Nitrogen Generators driven by Mixed-refrigerant J-T refrigerators and Gas Expansion cycles

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1. Introduction

Small liquid nitrogen (LN₂) generator is a convenient choice for field and remote users. Comparing with Stirling/G-M cryocoolers, mixed-refrigerant J-T (MRJT) refrigerators and feed gas expansion cycles (Kapitza cycle, etc.) can be employed in small liquefiers with higher cooling power utilization efficiency and lower construction cost. However, detailed comparison of MRJT and Kapitza types of LN₂ generators are rarely reported. Therefore, the performance of MRJT and Kapitza types are compared, as a reference for the design of small liquefiers.

2. Process configuration

Both of the MRJT type and Kapitza type of LN₂ generators are employed for low-pressure (< 9.0 bar) pure N₂ liquefaction and air separation, respectively.

2.1 MRJT type LN₂ generator

- Based on propane precooled single-stage MRJT separation cycles
  - Driven by single-stage oil-lubricated compressors for normal refrigeration
  - Low pressure N₂ liquefaction and air separation.
  - Closed N₂ cycle to deliver cooling power from flammable mixture to air
  - Cooling power for top condenser is supplied by throttled liquid nitrogen.

2.2 Kapitza type LN₂ generator

- Based on R22 precooled single-stage Kapitza cycles
  - Driven by small air compressors and precooled by nonflammable R22 cycles

3. Thermodynamic analysis and comparison

3.1 Analysis methods and conditions

LN₂ output (\(q_{LN₂}\)), specific power consumption (SPC) and figure of merit (FOM) are objectives:

\[
SPC = \frac{W_{\text{comp}} + W_{\text{exp}}}{W_{\text{in}}} \\
FOM = \frac{c_p \times T_{\text{c}} \times \delta}{Q_{\text{in}} + W_{\text{comp}} + W_{\text{exp}}}
\]

Exergy losses:

- Heat exchanger minimum approaches: 3 K
- Maximum discharge temperature: 385.15 K
- Compressor effectiveness: 60% / 70%
- Outlet temperature of after cooler and feed gas temperature: 308.15 K
- The mixture composition shift and heat leak are ignored

3.2 Performance of MRJT type LN₂ generators

Table 1. Key operating parameters in MRJT type LN₂ generators

<table>
<thead>
<tr>
<th>Process</th>
<th>MRJT + Pure N₂ (A)</th>
<th>MRJT + Column (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>Main Precooling</td>
<td>Main Precooling</td>
</tr>
<tr>
<td>Compressor suction pressure (bar)</td>
<td>3.50 2.20</td>
<td>3.50 2.20</td>
</tr>
<tr>
<td>Compressor discharge pressure (bar)</td>
<td>17.00 12.50</td>
<td>17.00 12.50</td>
</tr>
<tr>
<td>Temperature before throttling (K)</td>
<td>98.00 308.15</td>
<td>98.00 308.15</td>
</tr>
<tr>
<td>Temperature after throttling (K)</td>
<td>90.43 252.67</td>
<td>90.43 252.67</td>
</tr>
<tr>
<td>Mass flow rate (g s⁻¹)</td>
<td>5.70 2.60</td>
<td>5.70 2.60</td>
</tr>
</tbody>
</table>

Fig. 5. T-Q diagram of MRJT refrigerator

3.3 Performance of Kapitza type LN₂ generators

Table 2. Key operating parameters in Kapitza type LN₂ generators

<table>
<thead>
<tr>
<th>Process</th>
<th>Kapitza A, prep (A)</th>
<th>Kapitza A, prep (C)</th>
</tr>
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<tr>
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Fig. 7. performance of Kapitza + Pure N₂

3.4 Performance comparison of MRJT and Kapitza types of LN₂ generators

Both for small scale low pressure (< 9.0 bar) N₂ liquefaction and air separation:

- The efficiencies (FOM) of MRJT types are obviously superior to Kapitza types
- The total compressor displacements of MRJT types are smaller than Kapitza types
- Exergy losses in after cooler and nonideal expander are large in Kapitza types

Therefore, MRJT types might be more favorable for small LN₂ generators

4. Summary and discussion

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Fig. 10. Key parameter comparison