Numerical and Experimental Studies of Two-stage Pulse Tube Cryocoolers Working Around 20K

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  ● System configurations
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Introduction

◆ Small scale cryocoolers working at liquid hydrogen temperature has many important applications

- Space exploration
- Mid-infrared sensors
- Cooling superconductors
- Low temperature physics
Introduction

- G-M or G-M type pulse tube cryocooler
- Multi-stages Stirling cryocooler

- Regular Maintenance
- Oil Lubricated Compressor

- Linear compressor
- Low temperature displacer
Introduction

- Stirling type two stage pulse tube cooler working at 20 K

L. Yang et. al, thermally-coupled, 12.8 K

Q. Zhou et. al
13.9 K, 0.3 W @20K

✅ Low thermal efficiency
Introduction

◆ How to obtain a **high efficiency and compact** pulse tube cooler system?
◆ Warm displacers can be used in the two-stage pulse tube cryocooler

![Diagram of pulse tube cryocooler with components labeled 1 to 11.]

- **High Efficiency**
- **No moving parts at cold area**
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System configurations

◆ Two stage gas-coupled pulse tube cryocooler
◆ Dual-opposed stepped warm displacer configuration is adopted

a. Double inlet type

b. Stepped warm displacer type
Theoretical analyses

- Expansion acoustic power can be recovered
- An appropriate phase relationship between the pressure wave and volume flow rate can be realized

Phasors diagram for the stepped warm displacer
Numeric Model And Simulation

- Our simulation is based on a quasi-one-dimensional numeric model using the thermoacoustic theory and Sage 10 software.
- Geometric and operating parameters are selected according to the numerical calculation results.

<table>
<thead>
<tr>
<th>Components</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>First stage regenerator</td>
<td>i.d. 20.17 mm, length 60 mm, filled with 300# stainless steel mesh</td>
</tr>
<tr>
<td>First stage pulse tube</td>
<td>Annular, Outer diameter 16.4 mm, inner diameter 7.3 mm, length 70 mm</td>
</tr>
<tr>
<td>Second stage regenerator</td>
<td>i.d. 12.64 mm, length 50 mm, filled with HoCu₂</td>
</tr>
<tr>
<td>Second stage pulse tube</td>
<td>i.d. 7.3 mm, length 148 mm,</td>
</tr>
</tbody>
</table>

✓ Frequency: 30 Hz
### Numerical simulation results

- Expansion acoustic power can be recovered
- The dimensions of the phase shifter are optimized to obtain the highest efficiency and the results are shown in table
- An appropriate phase relationship between the pressure wave and volume flow rate can be realized

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Double inlet</th>
<th>Stepped warm displacer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic power input (W)</td>
<td>421</td>
<td>211</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>1.37</td>
<td>1.37</td>
</tr>
<tr>
<td>First stage cold end temperature (K)</td>
<td>45.9</td>
<td>45.3</td>
</tr>
<tr>
<td>No-load temperature (K)</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Recover acoustic power (W)</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Cooling power at 20 K(W)</td>
<td>1.45</td>
<td>1.47</td>
</tr>
<tr>
<td>Relative Carnot efficiency (based on the acoustic power input)</td>
<td>4.8%</td>
<td>9.7%</td>
</tr>
</tbody>
</table>
Experimental setup

- The system includes a moving-magnet linear compressor and a completely co-axial gas-coupled two stage pulse tube cooler
- The compressor uses dual-piston configuration to cancel vibration
- Two elastic membranes are used to eliminate the DC flow

Experimental systems using double inlet valve and inertance tube
Room temperature displacers

- The parameters are kept the same with the double inlet type
- Each ambient displacer is supported by four flexure springs with a total stiffness of 19 kN/m. The natural resonance frequency is 73.6 Hz
Experimental results and discussions

◆ A no-load temperature of 13.9 K

Temperature of the first stage and second stage cold end vs. frequency

Pressure ratio: 1.37
Mean pressure: 3.0 MPa
Experimental results and discussions

- With double inlet phase shifter, 1.1 W cooling power at 20 K can be obtained and the relative Carnot efficiency is only 3.85%
- While with stepped warm displacer phase shifter, it results in 1.06 W cooling power at 20 K and the relative Carnot efficiency reaches 6.5%. The optimum efficiency is far higher than the value of double inlet type.

Pressure ratio: 1.37
Frequency: 30 Hz

Cooling capacity with warm displacer as phase shifter
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➢ Conclusions
Thermal-coupled two-stage cryocooler

- At the first stage, an ultrahigh frequency operation of 100 Hz is utilized to precool the second stage for seeking a higher power density.
- At the second stage, a relative lower frequency of around 30Hz is used for improving system efficiency.
Numeric Model And Simulation

- Our simulation is based on a quasi-one-dimensional numeric model using the thermoacoustic theory and Sage 10 software.
- Geometric and operating parameters are selected according to the numerical calculation results.

<table>
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<tr>
<th>Components</th>
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<tbody>
<tr>
<td>First stage regenerator</td>
<td>i.d. 20.0 mm, length 35 mm, filled with 600# stainless steel mesh</td>
</tr>
<tr>
<td>First stage pulse tube</td>
<td>Diameter 10.0 mm, length 52 mm</td>
</tr>
<tr>
<td>Second stage regenerator</td>
<td>i.d. 20 mm, length 60 mm, filled with HoCu₂</td>
</tr>
<tr>
<td>Second stage pulse tube</td>
<td>i.d. 10.0 mm, length 122 mm,</td>
</tr>
</tbody>
</table>
Numerical simulation results

- The first stage provides 17-18 W cooling power at 77K to precool the second stage
- The efficiency of the system can be improved by 90% when using displacer as the phase shifter

<table>
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<th>Parameters</th>
<th>Double inlet</th>
<th>Stepped warm displacer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic power input at 1&lt;sup&gt;st&lt;/sup&gt; stage (W)</td>
<td>154</td>
<td>167</td>
</tr>
<tr>
<td>Acoustic power input at 2&lt;sup&gt;nd&lt;/sup&gt; stage (W)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Pressure ratio of second stage</td>
<td>1.26</td>
<td>1.32</td>
</tr>
<tr>
<td>First stage cold end temperature (K)</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>Precooling power (W)</td>
<td>17.1</td>
<td>18.7</td>
</tr>
<tr>
<td>Cooling power at 20 K(W)</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>Relative Carnot efficiency (based on the acoustic power input)</td>
<td>5.5%</td>
<td>10.2%</td>
</tr>
</tbody>
</table>
Experimental setup

- Co-axial configuration for each stage
- The thermal bridge is composed of 0.1 mm copper plates
- Test and more optimization are on the way

Linear compressor for the second stage
Linear compressor for the first stage

Experimental systems using stepped displacers
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Conclusions

- A two-stage gas-coupled pulse tube cooler system with a completely co-axial configuration is presented.
- A stepped warm displacer, working as the phase shifter for both stages, has been studied theoretically and experimentally.
- The experiments show that compared with double inlet type, the efficiency of the system improves by 70% with stepped warm displacer as the phase shifter.
- A thermal-coupled two stage pulse tube cooler has been developed.
THANKS

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