Study on the flow nonuniformity in a high capacity Stirling-type pulse tube cryocooler

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Contents

Flow Nonuniformity

- Motivation
- CFD models
- Flow Straighteners
  - Screens
  - Copper Slots
  - Transition Parts
- Summary
Motivation

In high capacity SPTC, flow nonuniformity is a major problem, which would decrease the performance of the cooler.

In this study, we focused on the flow distribution in the pulse tube.
A simplified 2-D CFD model has been established to study the flow field in the pulse tube with and without flow straighteners.

The flow straighteners used in the model is simplified as porous media.

Pressure-based, transient, axisymmetric model
Standard k-e, PISO, Green-Gauss cell based
CFD models

Temperature contours in the pulse tube. Without flow straighteners. There exists jet streaming in the pulse tube without the flow straightener.

Even though the model is simplified, it shows that the flow straightener has great impact on the temperature distribution in the pulse tube.

Temperature contours in the pulse tube. With flow straighteners. The flow distribution in the pulse tube are more uniform with the flow straightener.
Energy flow

In an ideal pulse tube cryocooler, the cooling capacity equals to enthalpy flow in the pulse tube.

While in the real system, the cooling capacity is affected by the entropy flow. A bad flow distribution in the pulse tube would generate much entropy, which can decrease the performance of the cooler.

So it has to use the flow straighteners to uniform the flow to decrease the entropy generation and increase the efficiency of the cooler.

\[
\langle p_d \dot{V} \rangle = \langle \dot{H} \rangle - T_m \langle \dot{S} \rangle
\]
Flow Straighteners

Three different groups of flow straighteners have been tested.

- **Screen**
  - At the ends of the pulse tube
  - **Group 1**

- **Copper slots**
  - At the ends of the pulse tube
  - **Group 2**

- **Transition parts**
  - Between the pulse tube and the inertance tube
  - **Group 3**
Flow Straighteners

<table>
<thead>
<tr>
<th>Flow straighteners</th>
<th>No.</th>
<th>conditions</th>
<th>geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screens (Group 1)</td>
<td>#1</td>
<td>0 screen</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td>5 screens</td>
<td>Diameter 60mm, thickness 1mm, 80 mesh</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>10 screens</td>
<td>Diameter 60mm, thickness 2mm, 80 mesh</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td>20 screens</td>
<td>Diameter 60mm, thickness 4mm, 80 mesh</td>
</tr>
<tr>
<td>Copper slots (Group 2)</td>
<td>#5</td>
<td>At the top of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm, porosity 27%</td>
</tr>
<tr>
<td></td>
<td>#6</td>
<td>At both ends of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm for each, porosity 27%</td>
</tr>
<tr>
<td></td>
<td>#7</td>
<td>At the bottom of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm, porosity 27%</td>
</tr>
<tr>
<td>Transition parts (Group 3)</td>
<td>#8</td>
<td>Long tapered transition part</td>
<td>Bottom inner diameter 60mm, top inner diameter 15mm, length 100mm</td>
</tr>
<tr>
<td></td>
<td>#9</td>
<td>Short tapered transition part</td>
<td>Bottom inner diameter 60mm, top inner diameter 15mm, length 40mm</td>
</tr>
<tr>
<td></td>
<td>#10</td>
<td>Short transition with stainless steel</td>
<td>Bottom diameter 60mm, length 23mm, porosity 26.8%</td>
</tr>
</tbody>
</table>

Detailed information

The detailed geometric parameters of the flow straighteners are shown in the table.
It is difficult to measure the flow nonuniformity in the pulse tube.

The temperature is used as an indication of the flow distribution.

Without any screens, there exist large jet streaming in the pulse tube. The temperature in the middle of the pulse tube is similar with the cold heat exchanger.
Copper slots

Temperatures along the cooler and circumferential temperatures in the regenerator and the pulse tube

The no-load temperature is around 80K. The performance of the cooler is better than that without any screen, but is worse than that with screens.

The circumferential temperatures in the pulse tube vary a lot with copper slots putting at different places.

Also, the circumferential temperatures in the regenerator can be affected by the slots. They are not good flow straighteners. They may cause extremely large circumferential temperature difference. Which can decrease the performance of the cooler.
Transition part

Temperatures along the cooler and circumferential temperatures in the regenerator and cooling capacity

The circumference temperature difference in the regenerator is low with a long transition part. Which indicates a more uniform flow distribution.

The transition between the pulse tube and the inerterance tube is also important for the flow distribution. With the long transition part, the no-load temperature of the cooler decreases from 73K to 63K.

The cooling capacity of the cooler increases from 50W to 130W @80K.
Comparison

<table>
<thead>
<tr>
<th>Flow straighteners</th>
<th>No.</th>
<th>conditions</th>
<th>geometry</th>
<th>No-load temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screens (Group 1)</td>
<td>#1</td>
<td>0 screen</td>
<td>-</td>
<td>91.5K</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td>5 screens</td>
<td>Diameter 60mm, thickness 1mm, 80 mesh</td>
<td>70.1K</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>10 screens</td>
<td>Diameter 60mm, thickness 2mm, 80 mesh</td>
<td>68.6K</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td>20 screens</td>
<td>Diameter 60mm, thickness 4mm, 80 mesh</td>
<td>70.7K</td>
</tr>
<tr>
<td>Copper slots (Group 2)</td>
<td>#5</td>
<td>At the top of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm, porosity 27%</td>
<td>75.6K</td>
</tr>
<tr>
<td></td>
<td>#6</td>
<td>At both ends of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm for each, porosity 27%</td>
<td>76.2K</td>
</tr>
<tr>
<td></td>
<td>#7</td>
<td>At the bottom of the pulse tube</td>
<td>Diameter 60mm, thickness 7mm, porosity 27%</td>
<td>81.7K</td>
</tr>
<tr>
<td>Transition parts (Group 3)</td>
<td>#8</td>
<td>Long tapered transition part</td>
<td>Bottom inner diameter 60mm, top inner diameter 15mm, length 100mm</td>
<td>62K</td>
</tr>
<tr>
<td></td>
<td>#9</td>
<td>Short tapered transition part</td>
<td>Bottom inner diameter 60mm, top inner diameter 15mm, length 40mm</td>
<td>73.4K</td>
</tr>
<tr>
<td></td>
<td>#10</td>
<td>Short transition with stainless steel</td>
<td>Bottom diameter 60mm, length 23mm, porosity 26.8%</td>
<td>73K</td>
</tr>
</tbody>
</table>

It can be seen that without any flow straighteners, the no-load temperature is around 91K. While with the screens and a proper transition part, the no-load temperature decreases to 62K.
Copper screens are good choices as the flow straighteners. It can uniform the flow distribution in the pulse tube and increase performance of the cooler. But in large capacity SPTC, the performance of the cooler is not very sensitive to the thickness of the screens.

Copper slots could not be used as flow straighteners. It is not a good choice, even though it’s better than a hollow tube.

The transition part between the pulse tube and the inertance tube also matters. With a smooth transition part, the cooler would achieve a high cooling capacity.
Thanks for your attention!

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