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

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Abstract. High capacity Stirling-type pulse tube cryocoolers (SPTC) have promising applications in high temperature superconductive motor and gas liquefaction. However, with the increase of cooling capacity, its performance deviates from well-accepted one-dimensional model simulation, such as Sage and Regen, mainly due to the strong field nonuniformity. In this study, several flow straighteners placed at both ends of the pulse tube are investigated to improve the flow distribution. A two-dimensional model of the pulse tube based on the computational fluid dynamics (CFD) method has been built to study the flow distribution of the pulse tube with different flow straighteners including copper screens, copper slots, taper transition and taper stainless slot. A SPTC set-up which has more than one hundred Watts cooling power at 80 K has been built and tested. The flow straighteners mentioned above have been applied and tested. The results show that with the best flow straightener the cooling performance of the SPTC can be significantly improved. Both CFD simulation and experiment show that the straighteners have impacts on the flow distribution and the performance of the high capacity SPTC.

1. Introduction

The high capacity pulse tube cryocooler has promising applications in high temperature superconductive motor and gas liquefaction. However, the high capacity SPTC is different from the conventional small scale SPTC due to the flow nonuniformity, which decreases the efficiency of the high capacity SPTC [1]. Therefore, it is important to further study the flow nonuniformity in the high capacity SPTC to achieve a high efficiency [2, 3].

Many researchers have found this issue and paid attention to the flow nonuniformity. However, most of them studied on the flow nonuniformity in the regenerator. Gromoll [4], Ercolani [5], Dietrich [6] and Hu [7, 8] used copper and brass screens filled in the matrix to increase the transverse thermal conductivity, which can decrease the temperature inhomogeneity and increase the efficiency of the
SPTC. Imura [9] studied the influence of screens with different porosity on temperature inhomogeneity. However, only a few of them studied the flow nonuniformity in the pulse tube, which affects the efficiency of the cooler a lot. Potratz [10] used CFD simulations to study the flow transitions. Chen [11], Gu [12], Rout [13], Zhi [14] used numerical method to study the pulse tube. More research is needed to study the flow in the pulse tube.

In this paper, CFD simulations have also been conducted to investigate the pulse tube with and without flow straighteners. Experiments have been conducted on a high capacity SPTC to study the influence of the different flow straighteners (copper screens, copper slots, taper transition and taper stainless slots) on the flow distributions in the pulse tube.

2. CFD modeling

The CFD model based on Fluent 15 software is focused on the flow in the pulse tube with and without flow straighteners. The model is a two-dimensional axisymmetric representation of the cold head, the pulse tube, the heat exchanger and the transition. Standard k-epsilon method has been adopted to calculate the viscous term. Although this method is not as good as SST k-ω method when considering turbulence, the difference is not big when calculate the pulse tube model [15]. The heat exchanger is treated as homogenous and simplified as porous media model. The flow resistance coefficient of the porous media is calculated by empirical formula $f_r = \frac{129}{Re} + 2.91Re^{-0.103}$ [16]. Pressure-implicit with splitting of operators (PISO), which is good for calculating the alternating flow, has been adopted to solve the model.

The pressure wave and the mass flow rate are governed by $p = p_a \cos(\omega t)$ and $m = m_a \cos(\omega t + \theta)$. The pressure is measured. The mass flow rate and the phase angle are calculated by SAGE software. The charge pressure is 2.5 MPa. The frequency is 60 Hz. The pressure and mass flow rate at various locations are shown in figure.1. Fixed time step size of 0.000167 is adopted. The mass and energy convergence criteria are $10^{-3}$ and $10^{-6}$. The temperature contours predicted by the CFD model are shown in figure.2. The flow straighteners are simplified as homogenous porous part. In reality, it’s not homogenous but it is hard to be represented in the simulation model. The figure shows that with flow straighteners, the flow in the pulse tube can be more homogenous. Flow straighteners in the pulse tube achieve better flow distributions. The figure of merit for the pulse tube increases 17%.

![Figure 1. Pressure and mass flow at various locations.](image-url)
Figure 2. Temperature contours in the pulse tube: (a) original pulse tube, (b) with flow straighteners at both ends of the pulse tube.

3. Experimental set-up

The high capacity SPTC experiment set-up is shown in figure 3. The compressor is a linear compressor (CFIC 2S297W) with dual-opposed pistons. Platinum resistors ($\pm 0.1$ K) are used to measure the temperature at the cold head and the transition part. Pressure sensors (Endevco, 0.1%, sampling rates 10000/s) are used to measure the pressure at the inlet of the regenerator and the transition part. The system is generally operated at a charging pressure of 2.5 MPa and a frequency of 60 Hz.

![High capacity SPTC experiment set-up](image)

Figure 3. High capacity SPTC experiment set-up: (1) compressor (2) after cooler (3) regenerator (4) cold head (5) pulse tube (6) heat exchanger (7) transition part (8) inertance tube (9) reservoir.

Different flow straighteners, shown in figure 4, are used to decrease the flow nonuniformity. The copper screens and the copper slots are placed at the end of the pulse tube to enhance the flow distribution, while the taper transition and taper stainless slot are mounted between the pulse tube and the inertance tube to straighten the flow. The different flow straighteners are categorized into three groups as shown in table 1 and tested separately. The input power is held constant. When the short transition replaces the long transition, the inertance tube is longer to compensate the volume.
4. Experimental results

4.1 Screens

Screens have been used by many researchers as flow straighteners. It has been proved an effective method in small capacity SPTC. Various numbers of screens have been tested and the temperatures at various locations along the cooler are shown in figure 5. It shows that with 10 screens in the pulse tube the cooler achieves a slightly lower no-load temperature than with other number of screens. The lowest performance configuration is with no screens in the pulse tube. Without any flow straighteners, jet flow occurs in the pulse tube [17, 18]. The mixture of the high temperature gas and the low temperature gas causes great entropy generation and great loss. Which causes an increase of 30 K of the no-load temperature in our experiment. The results show screens in the pulse tube enable better flow distribution and better performance. The influence of screen thickness is less than in the small capacity SPTC, where a slightly changing of the screens would affect the performance a lot.
Table 1. Summary of the flow straightening configurations tested.

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

Figure 5. Temperatures along the cooler with various screens.

Figure 6. Temperatures along the cooler with slots at different locations.

4.2 Copper slots
Copper slots have also been used as flow straighteners and tested by experiment. The temperatures at different locations along the cooler with copper slots at the ends of the pulse tube are shown in figure 6. Even though the no-load temperatures appear almost the same, but the temperature distributions in the pulse tube and the regenerator are quite different. The temperature difference varies from 30 K to 86 K,
which means that the flow nonuniformity is great. Flow inhomogeneity causes great losses in the regenerator and in the pulse tube [19, 20]. The no-load temperatures with slots are higher than those with screens. Screens perform better than slots as flow straighteners.

**Figure 7.** Circumferential temperatures at the bottom of the pulse tube with copper slots at various locations.

**Figure 8.** Circumferential temperatures at the middle of the regenerator with copper slots at various locations.

### 4.3 Transition parts

The influence of the transition part between the pulse tube and the inertance tube on the performance has also been tested. Figure 9 contains the temperatures along the cooler with different transition parts. With the long tapered transition, the cooler can achieve a no-load temperature of 62 K, while with the short tapered transition or with the stainless steel slots, the cooler achieves only 73 K. The long transition part makes not only a more uniform flow distribution in the pulse tube, but also a more uniform flow distribution in the regenerator, as shown in figure 10. The circumferential temperature difference is small, which means a relative homogeneous flow field. The entropy generation is small, and thus the losses are small [21, 22]. As a result, the cooling power is 130 W at 80 K with the long transition part, about 80 W larger than those of using the other two transition parts.

**Figure 9.** Temperatures along the cooler with different transition parts.

**Figure 10.** Circumferential temperatures at the middle of the regenerator with various transition parts.
5. Conclusions

Different types of flow straighteners have been studied to investigate the influences on the flow distribution in the pulse tube of high capacity SPTC. CFD modeling has shown that the flow transition has great impacts on the flow distribution in the pulse tube. It is important to use flow straighteners to achieve a uniform flow distribution in the pulse tube. Three categories of flow straighteners have been tested on an existing large capacity SPTC. The conclusions are shown below.

(1) The screens are better choices to straighten the flow in the pulse tube and increase the performance of the cooler. The influence of screens thickness of the screens is less than in small scale pulse tubes.

(2) Copper slot performance is less than screens for flow straighteners.

(3) The transition part between the pulse tube and the inertance tube has great influence on the flow distribution. A better transition part can help the cooler achieve a higher cooling capacity, in our case, of around 80 W at 80 K.

To summarize, the combination of a better designed transition part and the screens would be the best choice to uniform the flow distribution in the pulse tube and to achieve a better performance of the cooler.

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