Design of a Two-Stage High Capacity Stirling Cryocooler Operating below 30K

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Introduction

The high capacity cryocooler working below 30K can find many applications in many fields such as superconducting motors, superconducting power and cryopump. Compared to the GM cryocooler, the free-piston Stirling cryocooler driven by linear compressor can achieve much higher efficiency and more compact structure. Because of these obvious advantages, we have designed a two stage free piston Stirling cryocooler system, which is driven by a moving magnet linear compressor with an operating frequency of 40 Hz and a maximum 5 kW input electric power.

Objective

- ❖ Develop a high efficient and compact cryocooler with the advantages of low maintenance and high reliability.
- ❖ The first stage of the cryocooler is designed to operate in the liquid nitrogen temperature and output a cooling power of 100 W.
- ❖ The second stage is expected to simultaneously provide a cooling power of 50 W below the temperature of 30 K.

Numeric Model

In order to achieve the best system efficiency, a numerical model based on the thermoacoustic model was developed to optimize the system operating and structure parameters. Meanwhile, the software SAGE is used for comparison.

Geometrical Configuration and Main Components

The system is composed of a linear moving magnet compressor, two regenerators, displacer, three heat exchangers and two expansion space.

- ◆ Regenerators
  - ✓ Both of the regenerators choose steel screen as the regenerator materials.
  - ✓ The diameter and length are selected according to the numeric calculation results.
- ◆ Heat exchanger and expansion space
  - ✓ The HXs are manufactured by EDM technology and made of copper.
  - ✓ At the first expansion space, the motion of displacer will bring cooling power for precooling the second regenerator, and it is also be able to provide some cooling power into the external environment.
- ◆ Displacer
  - ✓ Flexure bearing technology is used to support displacer.
  - ✓ The springs were installed inside the displacer.
  - ✓ After numerical optimization，four optimized flexure springs are used to supply the stiffness for supporting the displacer motion and forming suitable PU phase for the regenerator.
- ◆ Linear compressor
  - ✓ The moving-magnet structure is used in the motor.
  - ✓ The single-piston structure is utilized to form a more compact system and decrease the gas flow friction losses.
  - ✓ The compressor uses gas-bearing technology to ensure the clearance between the piston and the cylinder wall.
  - ✓ In the practical applications, the vibrations brought by single piston can be absorbed by using a passive oscillator or using two back-to-back cryocoolers.
  - ✓ It is expected to deliver more than 3 kW of acoustic power to the cryocooler and the a calculation efficiency is higher than 80%.

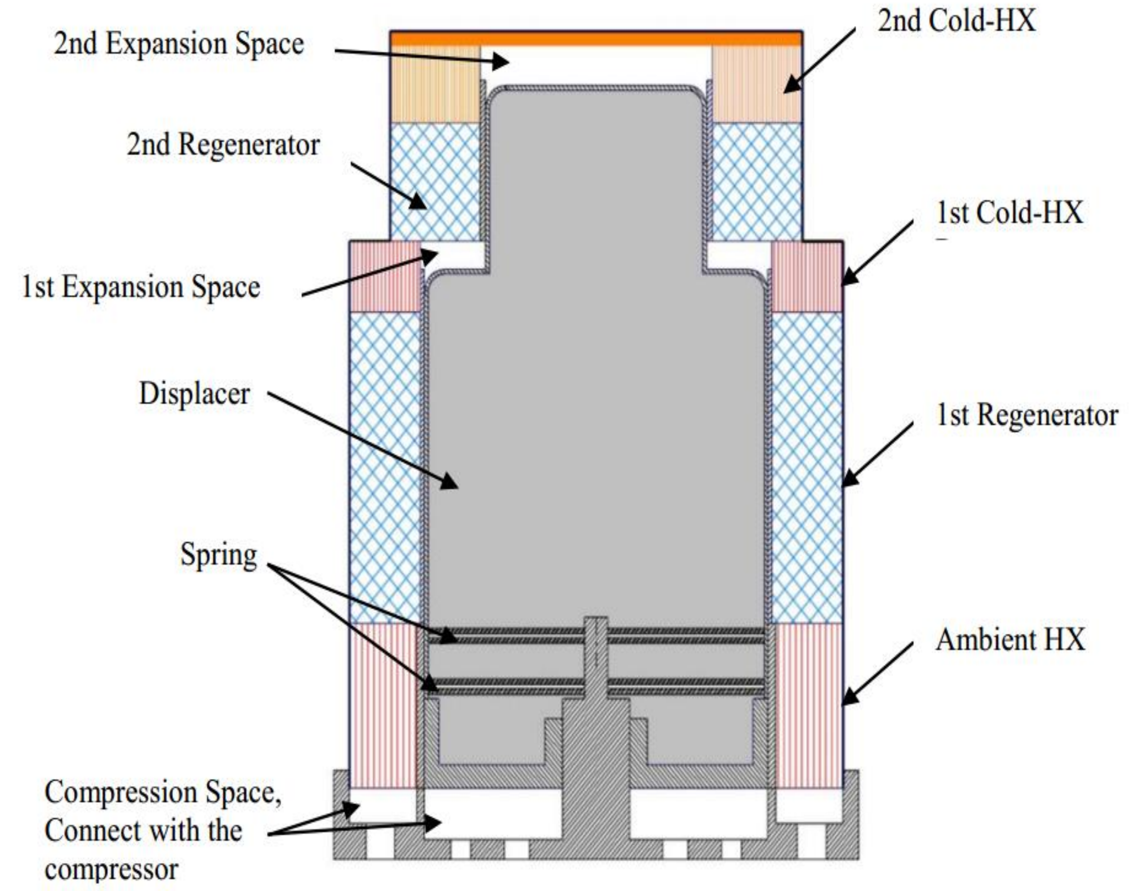

Fig.1 Illustration of the two-stage free piston Stirling cryocooler

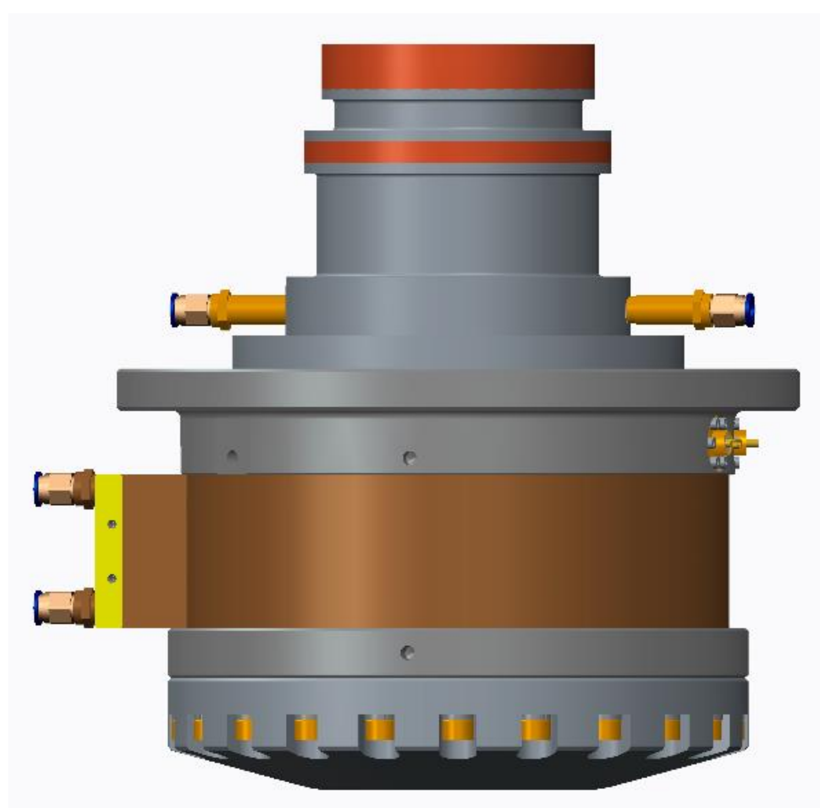

Fig.2 Preliminary Engineering Model of the two-stage free-piston Stirling-Cryocooler

Conclusions

- ◆ This paper presents the design of a two-stage free piston Stirling cryocooler, which is driven by a linear moving magnet compressor.
- ◆ The thermoacoustic theory was used to carry out the simulation and optimize the system operating and structure parameters.
- ◆ Simulation results show the cryocooler can reach a no-load temperature of 10K. A cooling power of 141W at 77K and a cooling power of 60W at 30K can be obtained simultaneously with a PV power of about 2.23kW, which means a relative Carnot efficiency of 44% and can satisfy the design goals.
- ◆ The system assembly is currently underway and some experimental results will be acquired very soon.

Simulation Results and Discussion

As shown in the Table1, the simulation results indicate that this system can meet the design requirements.

Table 2 shown the compressor design parameters, which is calculated through the cryocooler impedance and compressor mechanical governing equation.

Table 1. Details of the thermodynamic optimization results

Parameters	Values
Cooling power at the first stage	141W@77K
Cooling power at the second stage	60W@30K
Consumed acoustic power	2.23kW
Relative Carnot efficiency	44.25%
Ambient heat exchange temperature	35° C
Operating frequency	40Hz
Mean pressure	2.5MPa

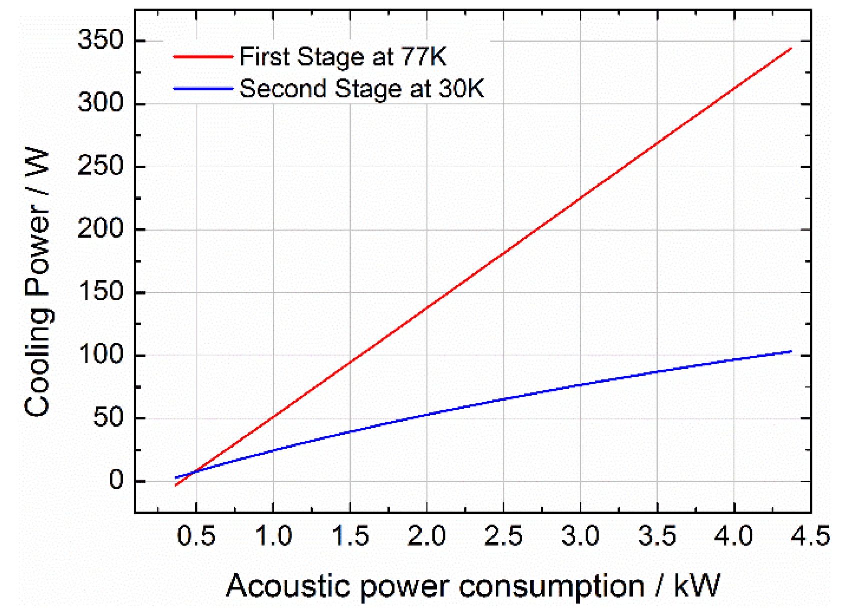

Fig.3 Cooling Power Vs. Input PV power

Table 2. Details of the linear compressor parameters

Parameters	Values
Swept volume by piston	200cm^3
Maximum input electric power	5kW
Operating Frequency	35-55Hz, depend on the cryocooler impedance
Weight	≤50kg
Efficiency	≥80% at typical cryocooler impedance
Piston maximum displacement	15mm

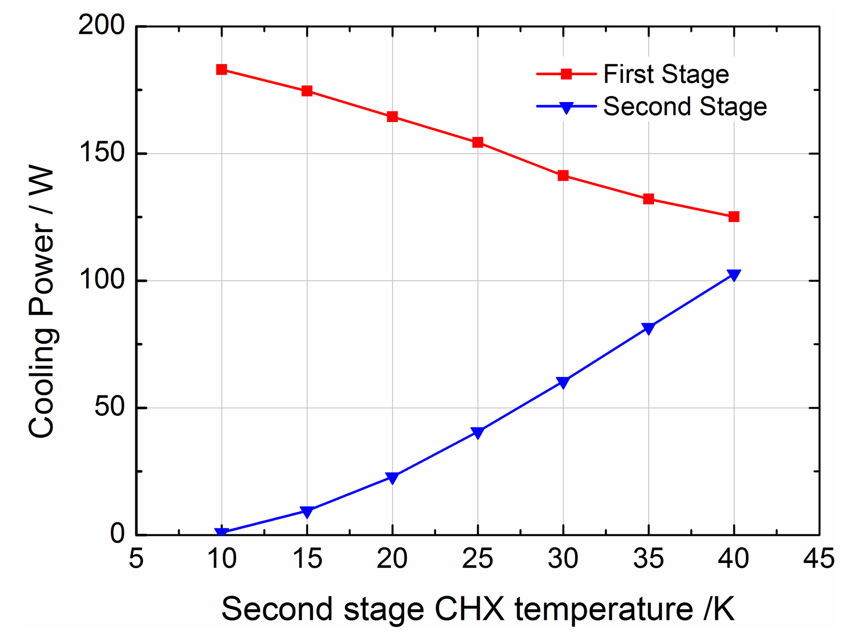

Fig.4 Performance at different 1st HX temperature

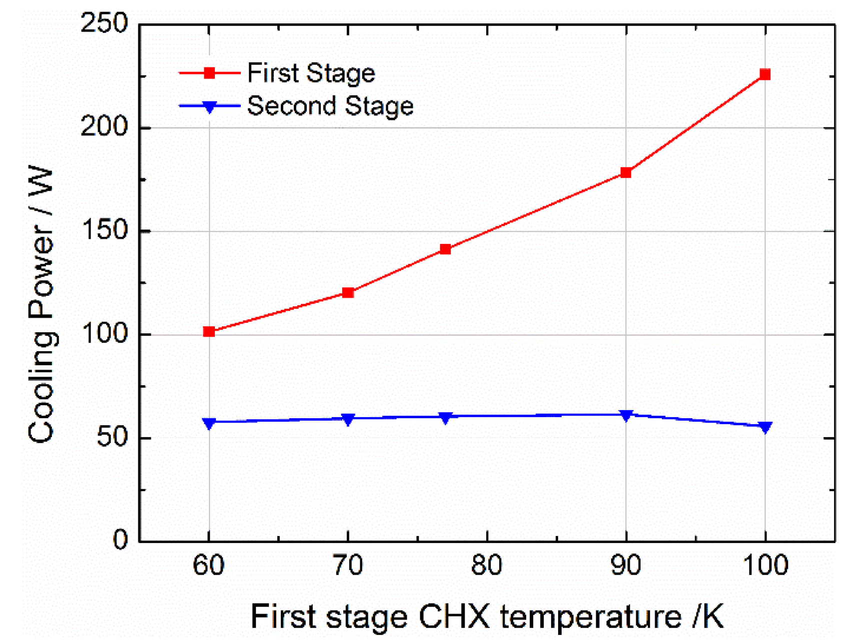

Fig.5 Performance at different 1st HX temperature

The Fig.4 shows the no-load 2nd cold Hx temperature can reach 10K and the cooling power at first stage decrease when the 2nd Hx temperature increase. But the change of 1st Hx temperature hardly affects the performance of the second stage, as shown in Fig.5.

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