IOP Conf. Series: Materials Science and Engineering **278** (2017) 012043 doi:10.1088/1757-899X/278/1/012043

Cool down time optimization of the Stirling cooler

M Xia[1], X P Chen[1], H Y Li[1], Z H Gan[2]

[1] Department of infrared detector, Kunming Institute of Physics, Kunming 650217, China,
[2] Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China

Email: gan_zhihua@zju.edu.cn

Abstract. The cooling power is one of the most important performances of a Stirling cooler. However, in some special fields, the cool down time is more important. It is a great challenge to improve the cool down time of the Stirling cooler. A new split Stirling linear cryogenic cooler SCI09H was designed in this study. A new structure of linear motor is used in the compressor, and the machine spring is used in the expander. In order to reduce the cool down time, the stainless-steel mesh of regenerator is optimized. The weight of the cooler is 1.1 kg, the cool down time to 80K is 2 minutes at 296K with a 250J thermal mass, the cooling power is 1.1W at 80K, and the input power is 50W.

1. Introduction
The cooling power is the most important performance for a Stirling cooler. But in some special field, the cool down time is more important. Usually, the cool down time of J-T cooler is shorter than that of the Stirling cooler[1]. Compared with the J-T cooler, Stirling cooler has several advantages:

a. The Stirling cooler can run continuously;
b. The running process of the Stirling cooler is a close thermodynamic cycle, which decreases the workload of maintenance;
c. The Stirling cooler can improve the performance of an infrared detector because of the tiny change of the temperature in the cold head.

A new Stirling cooler SCI09H was developed by us for the rapid cooling field. The cooler was designed by the methods of the analysis theory, numerical calculation and experiment study. In order to shorten the cool down time, the structure of the SCI09H cooler included a variable dimension expander cylinder, a small regenerator and a moving coil linear compressor. The weight of a cooler is 1.1 Kg, the cool down time to 80K is 2 minutes at 296K with a 250J thermal mass, the cooling power is 1.0W at 80K, and input power is 50W.

2. The theoretical analysis
The important parts affecting the cool down time in a cooler includes the mesh regenerator, the regenerator tube, the cold finger, the thermal mass and the cooling power[2]. The cold finger and the regenerator are shown in figure 1.

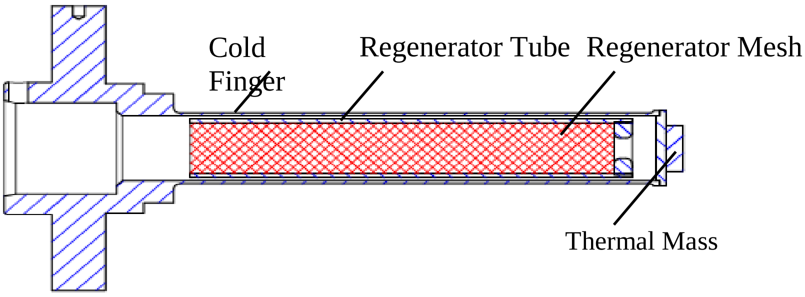

Figure 1. The cold finger and the regenerator of the cooler SCI09H

Assuming that the temperature of the cold finger, the regenerator tube and the regenerator are linear when the temperature of cold head changed from T_0 (the environment temperature) to 80K. When the temperature of cold head cooled down from T_0 to T, the average temperatures of the regenerator and the cold finger should be $(T_0+T)/2$. The temperature of part changed, heat energy will be released in quantity such as

$$\mathrm{d}J = \mathrm{c_m}(T) m \mathrm{d}T \tag{1}$$

where J is heat, $\mathrm{c_m}$ is mass specific heat capacity, T is temperature, m was mass.

Assuming that the cooling power $Q(T)$ is a function temperature.

$$Q(T)\,\mathrm{d}t = \mathrm{d}J \tag{2}$$

Equation (3) should be obtained by substitution of equation (1) into equation (2) by adding the summation of heat of cold finger, regenerator tube, regenerator and thermal mass,

$$Q(T)\,\mathrm{d}t = \left(\mathrm{c_R}\frac{(T_0+T)}{2}m_\mathrm{R} + \mathrm{c_{RT}}\frac{(T_0+T)}{2}m_\mathrm{RT} + \mathrm{c_F}\frac{(T_0+T)}{2}m_\mathrm{F}\right)\mathrm{d}T + \mathrm{c_{load}}(T)m_\mathrm{load}\mathrm{d}T \tag{3}$$

where subscript R is the mesh of regenerator, subscript RT is the tube of regenerator, subscript F is cold finger, and subscript load is thermal mass. When the temperature of cold head cooled down to T, the cool down time should be

$$t = \int_{T0}^{T1} \frac{\mathrm{c_R}((T_0+T)/2)m_\mathrm{R} + \mathrm{c_{RT}}((T_0+T)/2)m_\mathrm{RT} + \mathrm{c_F}((T_0+T)/2)m_\mathrm{F} + \mathrm{c_{load}}(T)m_\mathrm{load}}{Q(T)}\,\mathrm{d}T \tag{4}$$

In order to improve the cool down time, the cooling power $Q(T)$ must be large capacity, and the thermal capacity of the regenerator and thermal load must be small.

3. Design of the compressor

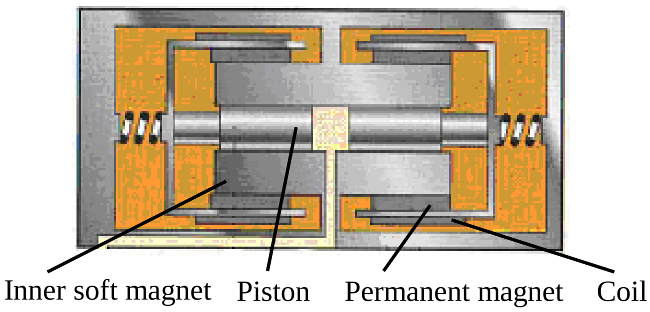

Figure 2. The structure of cooler SCI09H.

The linear compressor for Stirling cooler has two design options, the moving coil linear motor and the moving magnet linear motor. Compared with the moving magnet linear compressor, a moving coil linear motor is more efficient, more compact structure and lighter weight. But a moving magnet linear compressor has higher reliability than the moving coil linear compressor. In some special fields, the Stirling cooler need to be cooling down shortly, and with less mass. Therefore, the moving coil linear Stirling cooler is a better choice in those fields. The structure of the moving coil linear Stirling cooler SCI09H is shown in figure 2. The compressor is welded with laser welding, and the cooler has a storage life of at least 10 years.

When a moving coil linear compressor is running, the coil moves together with the piston. Thus, the magnetic flux density of the motor coil is changeable when piston is in the different position. The simulation results of the magnetic flux density analyzed with ANSYS software are shown in figure 3, and the results exhibited that the magnetic flux density value of the motor are between 0.4T and 0.5T.

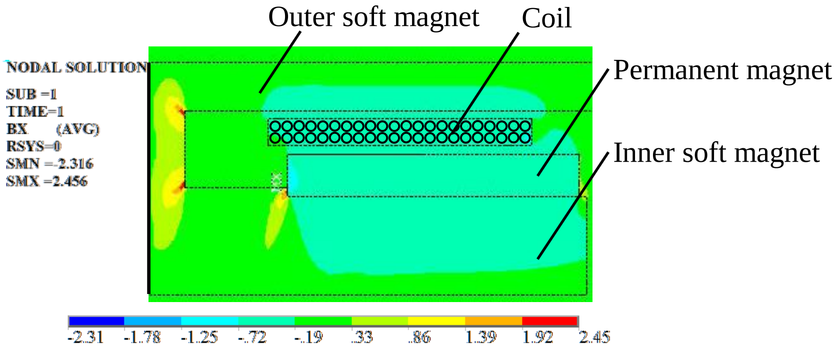

Figure 3. The result of magnetic circuit of compressor SCI09H.

The governing equations of a linear compressor includes the voltage equation and the force of motion equations[3] ,

$$V = RI + L\frac{dI}{dt} + Bl\frac{dx}{dt} \tag{5}$$

$$m\ddot{x} + k_{mag}x + (P - P_b)A = BlI \tag{6}$$

In equation (5), V is the applied electric voltage, R and L are the resistance and inductance of the motor coil, I is the current, B is the magnetic flux density, l is the length of coil, x is the displacement, t is the time. In equation (6), m is the moving mass of the compressor, k is the spring constant including mechanical, magnetic (in case of moving-magnet type motor) and backside gas spring effects, p is the pressure wave of the piston, P_b is the pressure of the backside of the piston.

In order to improve the reliability of the compressor, the flat springs are used. The coating of the piston is polyurethane. The diameter of compressor is 48mm. In figure 4, a CAD model of this new compressor is shown.

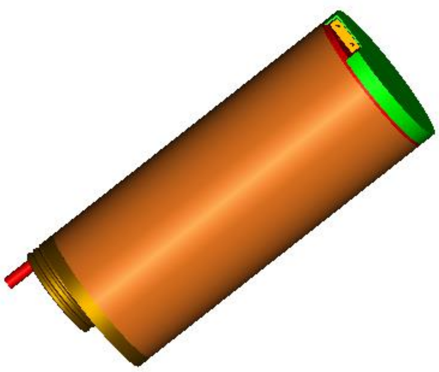

Figure 4. The CAD model of the new compressor.

4. Design of expander

In order to improve the cool down time, the cold finger we used is a small size one. The length of the regenerator is 35mm, and the diameter of the regenerator is 6.6mm. The material of the regenerator tube and cold finger are glass fibre and TC4 titanium alloy, respectively, which can decrease heat load of cold finger. In order to decrease the dead volume of the hot temperature volume, a stream guidance part is used in the base of expander, and the stream guidance part could also decrease flowing loss of helium. The stream guidance part plays a great role in improving cooler efficiency and shorting cool down time. Figure 5 is the structure of the expander.

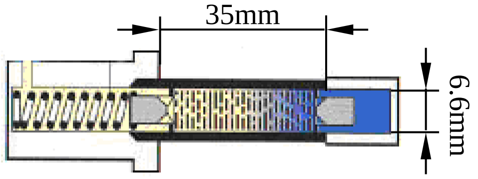

Figure 5. The structure of the expander SCI09H.

5. Design of the Stirling cryocooler

The FLUENT software was applied when the Stirling cryocooler was designed. Figure 8 is the analysis model of the Stirling cryocooler. Figure 8 shows that every part of Stirling cryocooler is a cylinder, and all parts are in alignment. Therefore, the analysis model is two dimensional (2D) axisymmetric.

In order to set a comparatively simplified and practical mathematic model, the basic assumptions are made as follows:

I. Two dimension (2D) axisymmetric flow and heat transfer;
II. Ideal and compressible gas and variable properties;
III. Innegligible axial heat conduction and flow resistance;
IV. Negligible clearance leakage between the cylinder and piston, or the cylinder and displacer;
V. Constant wall temperature of the hot and cold chambers;

The simulated results showe clearly the process of the flow and heat transfer in the cooler. Figure 6 shows the pressure contour of simulated results. The value of pressure is almost the same in every part in one moment, but there are some differences between the pressure of the two sides of the regenerator.

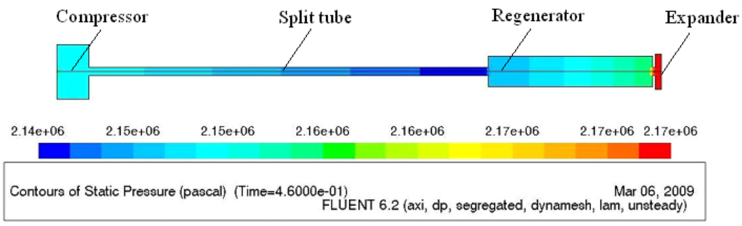

Figure 6. The pressure contour of simulated results.

Figure 7 shows the temperature contour of the simulated results. Temperature of the expander is about 77K when the temperature of the expander wall is 80K, and the temperature of the compressor is about 400K when the temperature of the compressor wall is 343K.

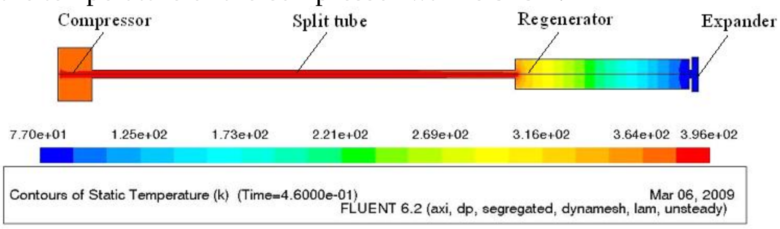

Figure 7. The temperature contour of the simulated results.

The relationship between pressure & time and volume & time in the compressor and expander is shown in figure 8. Pressures are almost the same wave in the compressor and expander. The volume wave is 125º ahead of the pressure wave in the compressor, while the pressure wave is 140º ahead of the volume wave in the expander.

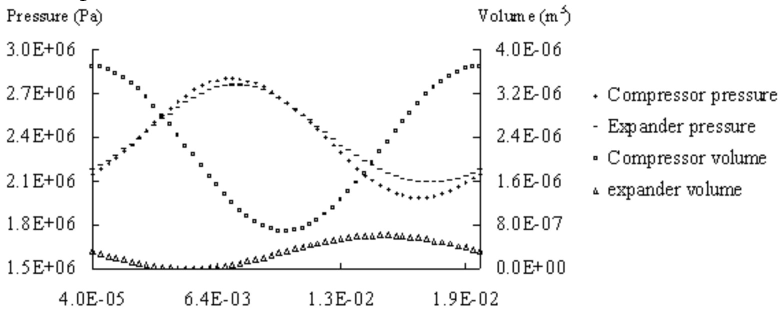

Figure 8. The relationship between pressure & time and volume & time in the compressor and expander.

Finally, the designing parameter of the cooler was that the diameter of the compression chamber was 8.5 mm, the compression stroke was 11 mm, the inner diameter of split tube was 1.8 mm, and the length of split tube was 150 mm.

6. Design of the controller

The main function of the controller is driving cooler and controlling temperature. The controller can generate a sine wave with variable voltage and variable frequency. Figure 9 shows the structure diagram of the controller which included three parts, the signal generator, the electric level transform and the filter. The merit of the controller is small size, light weight and high efficiency. The size of the controller is 72×60×20 mm. The weight of controller is less than 0.24 kg and the efficiency of the controller is 90%.

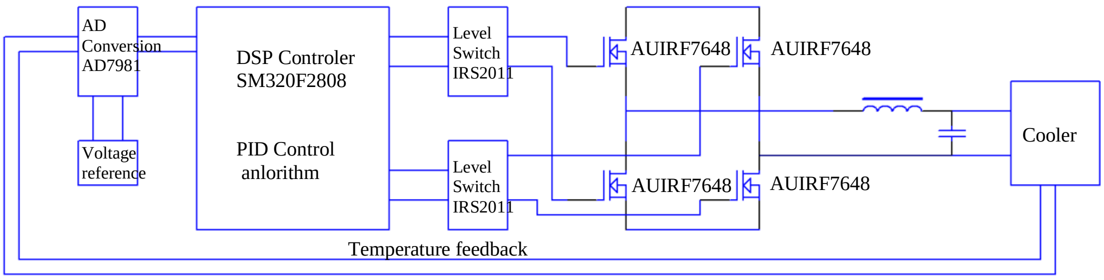

Figure 9 Structure diagram of the controller.

7. The performance test

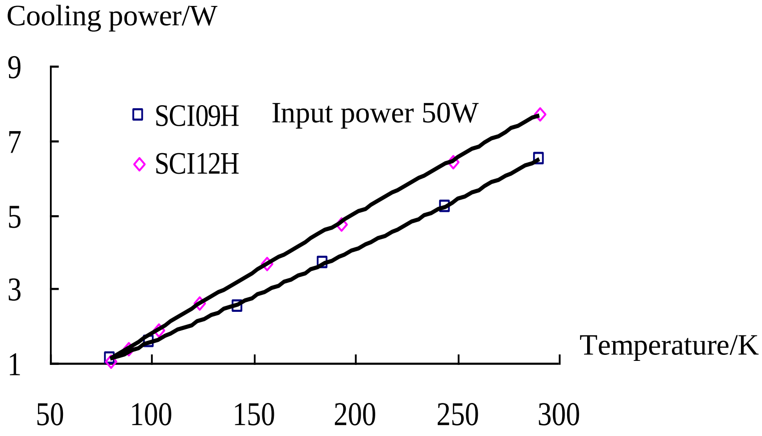

Figure 10. The cooling power of the coolers SCI09H and SCI12H.

The coolers SCI09H and SCI12H were tested. The cooler SCI09H is the one with faster cool down time, and the cooler SCI12H is 1W moving magnet linear cooler. The size of cold finger is 6.6mm in cooler SCI09H and the size of cold finger is 13mm in the cooler SCI12H. Figure 10 shows the cooling powers of these two coolers with different temperature of the cold head in 50W electric power. The cooling powers of SCI12H and SCI09H are 7.7W and 6.7W with 293K of cold head temperature, respectively. The temperature of cold head decreases, the cooling power of the cooler will also decrease. When the temperature of the cold head is 80K, the cooling powers of two coolers are both equal to 1.1W.

The cool down time of the coolers SCI09H and SCI12H with 250J heat mass are shown in figure 11. The cool down time of the coolers SCI09H and SCI12H is 140s and 204s, respectively. The cool down time of the cooler SCI09H is shorter than that of the cooler SCI12H in spite of the equal cooling powers in two coolers, because the regenerator of the cooler SCI09H is smaller than that of the cooler SCI12H.

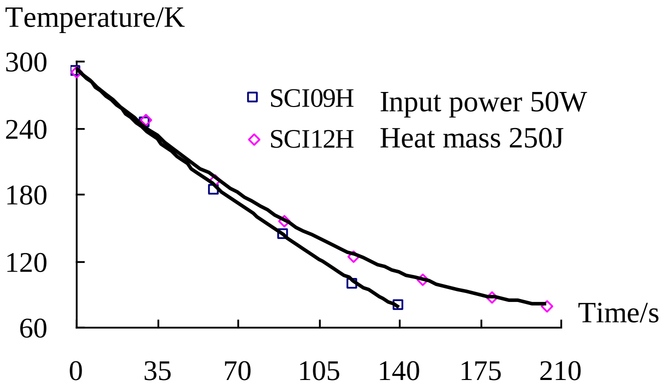

Figure 11. The cool down time of the coolers SCI09H and SCI12H.

8. Summary

A new model SCI09H of the split Stirling cooler was developed to improve cool down time in this study. The cooler's weight is 1.1 kg, the cool down time to 80K is 2 minutes at 296K with a 250J thermal mass, the cooling power is expected to be 1.0W at 80K, and the input power is 50W. The coolers SCI09H and SCI12H were tested. When the temperature of the cold head is 80K, the cooling powers of the two coolers are both equal to 1.1W. The cool down time of cooler SCI09H is shorter than that of the cooler SCI12H in spite of the equal cooling powers in these two coolers, because the regenerator of the cooler SCI09H is smaller than that of the cooler SCI12H.

References

[1] Chen XP, Xia M, Wang LY and Gan ZH The reliability development of miniature Stirling cryocoolers 2014 *Cryocoolers 18* (ICC Press, Boulder) pp 601–607

[2] Katz A, Segal V, Filis A, Haim ZB, Nachman I, Krimnuz E and Gover D Ricor's cryocoolers development and optimization for hot IR detectors 2015 *SPIE Proceedings* **9451** 945120

[3] Xia M and Chen XP Analysis of resonant frequency of moving magnet linear compressor of Stirling cryocooler 2010 Int. J. Refrigeration **33** 739