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Modelling and experimental study of a 700 g micro coaxial Stirling-type pulse tube cryocooler operating at 100-190 Hz

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Abstract. This paper presents the modelling and experimental study of a 700 g micro coaxial Stirling-type pulse tube cryocooler (SPTC) operating at 100-190 Hz. Neither double-inlet nor multi-bypass is used while the inertance tube with a gas reservoir becomes the only phase-shifter. A two-dimensional axis-symmetric CFD model of the micro SPTC is developed, in which the effect of frequency on the thermal process and cooling performance is studied in detail. Mixed regenerator matrices are used to decrease the irreversible loss, and a variety of approaches to minimize the overall cooler mass are attempted. The experimental results show that the SPTC could produce cooling power of 1.1 W at 77 K with an input power of 60 W.

1. Introduction

In recent years, the infrared applications such as space infrared detectors have developed rapidly. These applications need reliable low temperature environments to ensure the performance of them. Some applications such as micro satellite infrared detectors, the high temperature superconducting devices for space and the microelectronics mechanical systems require the cooling temperatures of 70-150 K and small refrigeration power (normally lower than 2 W). At the same time, the weight of the cryocoolers is limited and the time for cooling down should be shorter than several minutes. These years, as the representative of the new generation long life cryocoolers, the miniature of the pulse tube cryocoolers is crucial to the above applications [1-2].

Up till now, the research institutes of the miniature pulse tube cryocooler working over 100 Hz are Northrop Grumman Aerospace Systems (NGAS) and National Institute of Standards and Technology (NIST). The NGAS company has developed a 100 Hz coaxial prototype whose overall weight is only 0.8 kg in 2007. This can get a cooling capacity of 1.1W at 77 K with an input power of 50 W [3]. And this is further optimized later which can get a relative Carnot efficiency of 8 % at 80 K [4]. The NIST has conducted a more in-depth discussion on theoretical analysis, but there is still a big problem in the matching between the compressor and the pulse tube cold finger in the experiment. A 120 Hz coaxial miniature pulse tube cryocooler is designed by NIST. This can get a no-load temperature of 49.9 K with a 46.4 W input power and a cooling capacity of 3.35 W at 80 K [5].

In this paper, a 700 g micro coaxial Stirling-type pulse tube cryocooler (SPTC) operating at 100-190 Hz is investigated. A CFD model is built to show the effect of the frequency and mixed matrices to the thermal process and the cooling performance in detail. In addition, the miniature SPTC has been built and tested, and the targeted cooling performance is evaluated based on the available experimental data.

2. Design and simulation model

2.1. The design of the miniature SPTC

Figure 1 shows a schematic of the typical Oxford-type moving-coil dual-opposed linear compressor, in which the permanent magnet, the return iron and the moving coil form the magnetic structure of the linear motor.

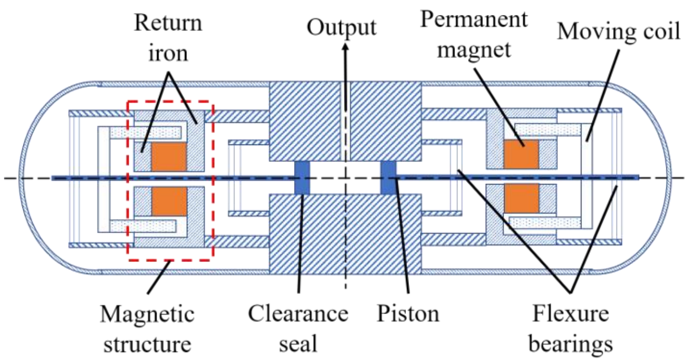


Figure 1. Schematic of an Oxford-type moving-coil dual-opposed linear compressor

The miniature linear compressor is developed based on the modified scaling method. The scaling factor need to be modified because of the limit of the performance, overall mass, and volume. For example, the target frequency of the design is over 100Hz. The scaling factor would be less than 0.55 because the operating frequency of the mid-sized linear compressor is about 55 Hz. If the scaling factor of the moving mass is still K^4, the moving mass will decrease 90.84%. The shaft of the piston will be less than 2 mm which is hard to manufacturing and assembling. Under such an occasion, the scaling factor of the moving mass should be changed. To limit the overall mass of the micro linear compressor, the scaling factor of the moving parts are changed to K^3. That of the length and diameter of the piston will change to K correspondingly.

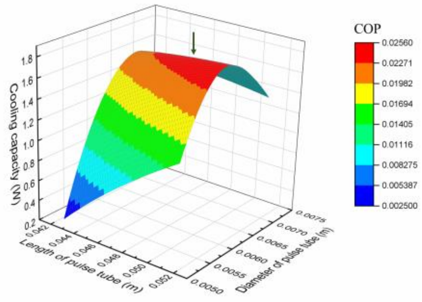


Figure 2. Influence of the dimension of the pulse tube to the performance

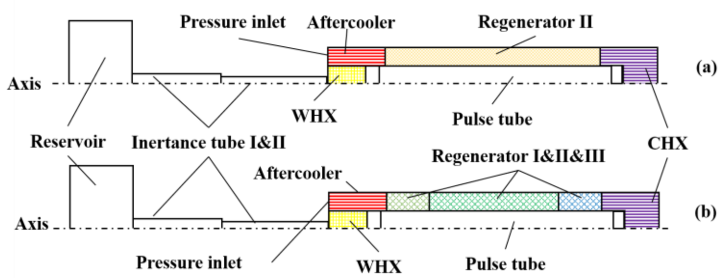


Figure 3. Schematic of the CFD model of the MPTC

The pulse tube cold finger can be designed based on the model developed in the same laboratory [6-7]. Figure 2 shows the basic optimization of the dimensional parameters. As the figure shows, the point that is point out by the arrow is the one whose cooling capacity and COP are more than 1.5 W and 2.2%, respectively. In order to minimize the volume and overall weight of the miniature pulse tube cryocooler (MPTC), the optimization of the structure and the arrangement of the MPTC is of great importance.

2.2. Simulation model

Table 1 shows the geometrical dimensions for each component in the MPTC based on the design above.

Table 1. Geometrical dimensions of the MPTC

Component	Radius (mm)	Length (mm)
Regenerator	13.4	37.3
Pulse tube	6.2	47.3
Inertance tube 1	2.5	1300
Inertance tube 2	4.5	2550
Reservoir	20	28

Figure 3 gives the schematic of the CFD model of the MPTC. The model consists of an aftercooler, a pulse tube, a regenerator, a cold heat exchanger, a warm heat exchanger, two inertance tubes and a reservoir. The regenerator is filled with SS304 matrices which is the porous zones. The external surface of the cold heat exchanger (CHX) is set to be adiabatic to achieve the no-load temperature. The wall temperature of the aftercooler and the warm heat exchanger (WHX) is 300 K as the reject temperature. The working fluid, helium, is assumed to be the ideal gas, and the matrices materials in the regenerator and the heat exchangers are stainless steel and copper, respectively. The thermal conductivity, viscosity and specific heat of both the helium and the solid materials are all temperature-dependent.

The micro linear compressor is simplified to be the oscillating pressure inlet in all the cases. The pressure inlet is given by: [8]

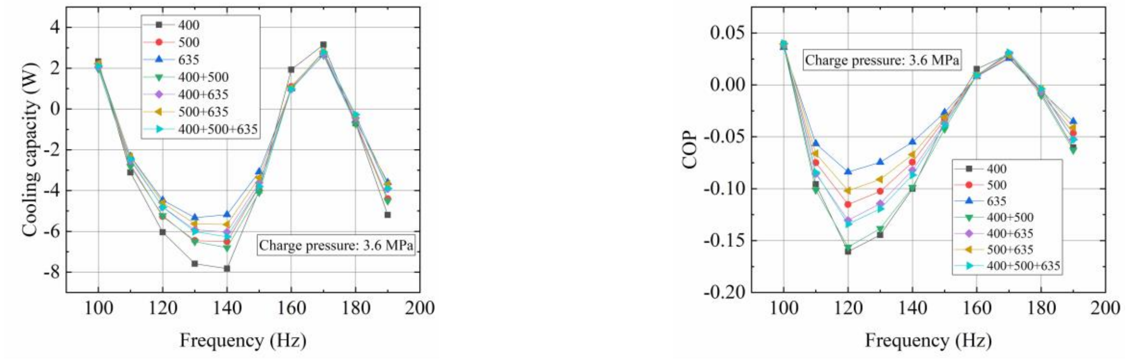
$$\mathrm{p} = p_0 + \Delta p \cdot \sin 2\pi f t \quad (1)$$

where f is the operating frequency, p_0 is the charging pressure, and Δp is the amplitude of the dynamic pressure at the inlet. Based on the basic design results of the MPTC, the value of the p_0 and Δp is fixed to be 3.6 MPa and 0.43 MPa, respectively.

3. Simulation results and discussions

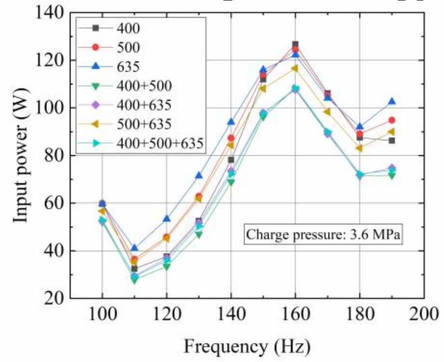
The performance of the SPTC has been investigated with different mesh and frequency. Because of the limit of the compressor, the maximum stroke of the piston is set as constant which means the pressure wave is the constant.

Figure 4 (a) shows the cooling capacity of the SPTC using different mesh. The ratio of different mesh has been optimized. The performance of the cases using the mix of 400-mesh SS screen turns out to be the highest. Figure 4 (b) shows that the SPTC with mixed of 400&500&635 matrices regenerator is the most efficient one if the regenerator is filled with the same kinds of SS screen. The performance of the regenerator filled with 500-mesh SS screen are slightly lower than the previous one. Figure 4 (c) shows the input power of each cases under different operating frequency. The cases with mixed mesh will need less PV power than the other cases when the cooling capacity is the same. Comparing the images in figure 4, there are 2 important frequency, that is 100 Hz and 170 Hz. The SPTC operating at these frequencies will have higher COP than other cases.



(a) (b)

Figure 4. Cooling performance of the SPTC with different mesh



(c)

Figure 4. Cooling performance of the SPTC with different mesh

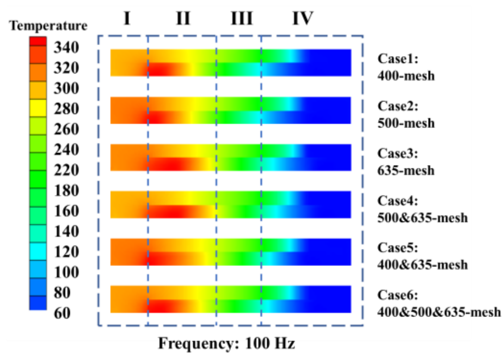


Figure 5. Temperature contours inside the cold finger in case 1-6

Figure 5 shows the temperature contours inside the cold finger in case 1-6 operating at 100 Hz. The contours are divided into four parts to make it easier to explain and understand. In part I, the temperature in case 2, 3 and 5 is higher than that in case 1. In part II, the high temperature area in the pulse tube is much more than that in case 1 and 2. And in part IV, the cold area is less than that in the other two cases.

Figure 6 shows the temperature contours inside the cold finger in case 7-16 using mixed matrix of 400&500&635 mesh. The high frequency has little impact on the temperature distribution inside the regenerator. In the case 7-16, the temperature distribution is almost the same. Only the no-load temperature is different. This figure shows that the optimal frequency is around 130-160 Hz.

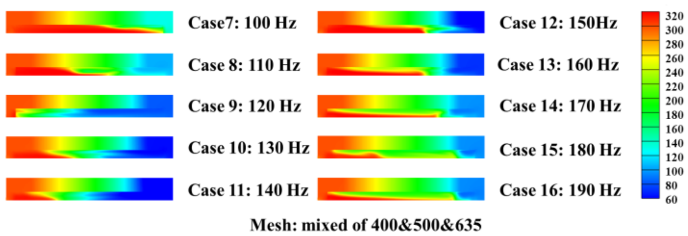


Figure 6. Temperature contours inside the cold finger in case 7-16

Figure 7 shows the experimental testing of the linear compressor coupling with pulse tube cold finger. The experiment is constructed with the linear compressor, the cold finger, the data acquisition system and the NF power supply. The cool down curve, the cooling capacity and the efficiency of the linear compressor are tested.

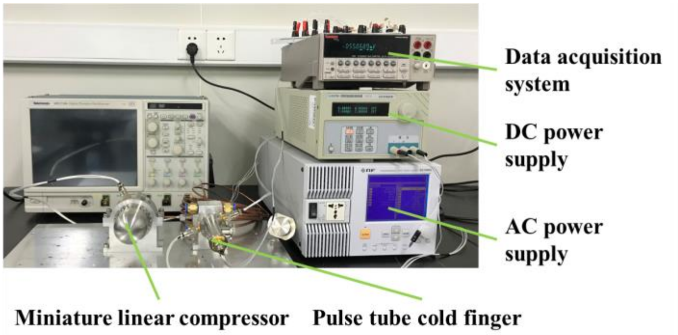


Figure 7. Temperature contours inside the cold finger in case 7-16

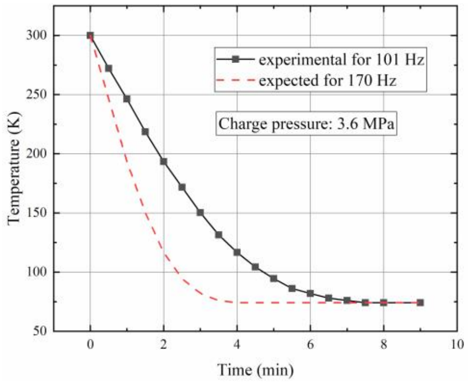


Figure 8. Cool down curve in the experimental testing

Figure 8 shows the cool down curves of the miniature pulse tube cryocooler using the linear motor designed above. It only cost 50 W and six minutes to cool down to 77 K. And the cooling capacity of the MPTC is 1.1 W and 1.4 W at 77 K when the operating frequency is 101 Hz and 170 Hz, respectively.

4. Conclusion

This paper presents the design and the simulation of a miniature single-stage coaxial pulse tube cryocooler. The overall weight of the MPTC is 700 g. The structure of the MPTC is re-designed to lose weight and make it more convenient to use. Neither double-inlet nor multi-bypass is used while the inertance tube with a gas reservoir becomes the only phase-shifter. A CFD model is built to investigate the effect of frequency on the thermal process and cooling performance is studied in detail. The optimal frequency is around 100 Hz and 170 Hz. A MPTC with mixed matrices is built to verify the theory and it can obtain a cooling capacity of 1.1 W and 1.4 W at 77 K when the operating frequency is 101 Hz and 170 Hz, respectively.

5. References

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Acknowledgments

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