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Investigation of a coaxial Stirling-type pulse tube cryocooler with the cooling capacity of 600 W at 77 K

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Abstract. This paper conducts the investigation of a coaxial Stirling-type pulse tube cryocooler (SPTC) with the cooling capacity of 600 W at 77 K, in which a two-dimensional CFD model is established and the effects of the flow are studied. With the aimed high cooling capacity, the flow straighteners at both inlet and outlet of the pulse tube become crucial to ensure the cooling performance by minimizing the turbulence flows in it. The interaction of the pulse tube cold finger and the linear compressor is investigated in view of that the match between them plays an important role in improving the cooling performance. In the experiment, the SPTC has a cooling capacity of 580 W at 77 K with the relative Carnot efficiency of 12%.

1. Introduction

In recent years, the superconducting technology has developed rapidly. Owing to the characteristics of the superconductor, which are zero resistance, high density current carrying, and anti-magnetic, the superconductor can be used in the electrical applications to increase the capacity and to reduce the losses. The high temperature superconducting (HTS) devices applied in the electrical applications use the cooling systems providing cooling power of 500-1000 W at 77 K so that the superconductor could work efficiently. The cryocooler is the key equipment for the cooling system. The Stirling-type pulse tube cryocooler (SPTC) has characteristics of long life and high reliability comparing to other types of cryocoolers, and it is one of the good choices to the cooling systems for the superconductors.

Zia [1] developed a 4-kW electrical input linear motor driven pulse tube cryocooler (PTC) which can provide a refrigeration power of over 200 W at 80 K when the operating frequency is 60 Hz. In 2008, Praxair reported [2] a PTC with a refrigeration capacity of 1 kW at 77 K. The PTC is then used in the cooling system for HTS cable. In 2010, the SPTC was tested based in the operation in HTS cable application at Bixby Road substation in Columbus. This PTC has been running without any major concerns for about 7000 hours [3]. Later in 2015, Caughley et al. developed a PTC which can produce 480 W cooling power at 77 K. They used three of the previous PTC to develop a PTC with cooling capacity of 1270 W at 77 K [4]. In 2016, Chart Inc. reported that they had designed a 650 W



pulse tube cryocooler with the input power of 15 kW. It could reach 11% of Carnot efficiency at 80 K [5].

In this paper, a SPTC with the cooling capacity of 600 W at 77 K is investigated. The effects of the geometrical parameters to the performance are studied. The interaction of the pulse tube cold finger and the linear compressor is investigated in view of the fact that the match between them plays an important role in improving the cooling performance. The CFD model is established to study the flow and optimize the SPTC. The flow inside the pulse tube cold finger are studied and compared between the coaxial and in-line SPTC. Based on the analysis, an optimal case is chosen to be tested.

2. SPTC Design and numerical model

Figure 1 shows a schematic of a coaxial Stirling-type pulse tube cryocooler with a cooling capacity of 600 W at 77 K with its main components including a compressor, a connecting tube, two warm heat exchangers, a cold heat exchanger, a pulse tube, a regenerator, an aftercooler, two inertance tubes and a reservoir. The geometries of the SPTC including the geometry and the operating parameters are all calculated and optimized by the numerical simulation method developed in the same laboratory [6-7].

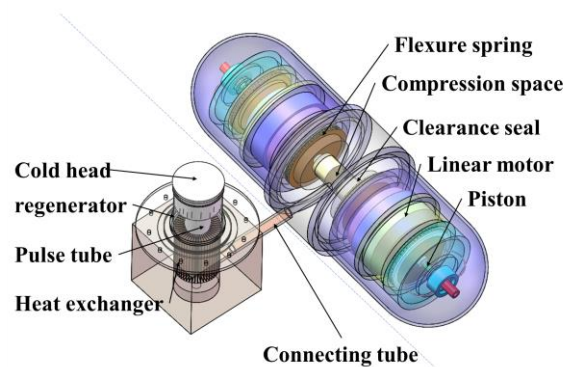


Figure 1. Schematic of a PTC

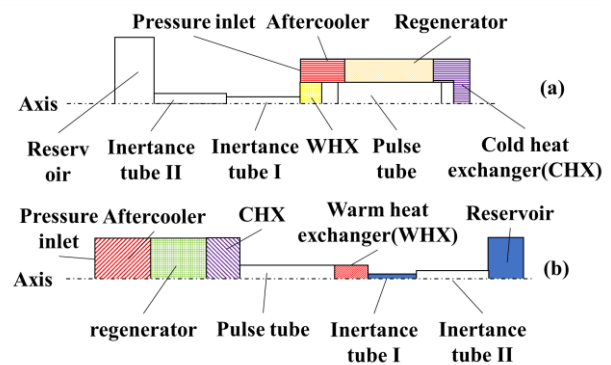


Figure 2. Schematic of the CFD model for SPTC

Figure 2 gives the CFD model of the SPTC. The Geometrical dimensions and boundary conditions of the components are given by table 1.

Table 1. Geometrical dimensions and boundary conditions

Component	Radius/mm	Length/mm	Boundary condition
Aftercooler	42.5	20	$T_w=300$ K
Regenerator	42.5	55	Adiabatic
CHX	42.5	45	$T_w=77$ K
Pulse tube	21	73	Adiabatic
WHX	21	10	$T_w=300$ K
Inertance tube 1	5	2017	$T_w=300$ K
Inertance tube 2	8.5	4647	$T_w=300$ K
Reservoir	10	35	$T_w=300$ K

The charge pressure and the operating frequency are set to be 2.58 MPa and 50 Hz, respectively. The linear compressor in the model is modeled as the pressure inlet. The inlet pressure wave can be defined using the User Defined Function [8]. So, the inlet pressure wave can be given by [8]:

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

Where the amplitude of the dynamic pressure Δp is calculated to be 0.915 MPa using the one-dimensional model. f is the operating frequency. p_0 is the charge pressure of the whole system and is set to be 2.58 MPa.

3. Results and discussions

3.1. The match between the compressor and the cold finger

Figure 3 shows the influence of the parameters of piston to the cooling performance. It is much easier to get a higher cooling capacity if the surface of the piston is larger. But the coefficient of performance (COP) of the pulse tube cryocooler will decrease if the area of the compression surface is over 0.012 m^2 . It can be figured out that there exists a point that the surface is less than 0.01 m^2 , and the efficiency is acceptable. In our cases, the diameter of the piston is set to be 100 mm as shown in figure 3 by the black dashed line. The cooling capacity can reach about 750 W if the stroke is more than 12 mm. At the same time, the COP of the cooler will be only about 5%. This simulation is conducted using the same cold finger, the similar COP is achieved whatever the changes are conducted to the compressor. The compressor will influence the performance of the cryocooler. The dimensions of the compressor will determine the maximum cooling capacity and the range of the COP, but the key influence factor of the performance is still the pulse tube cold finger.

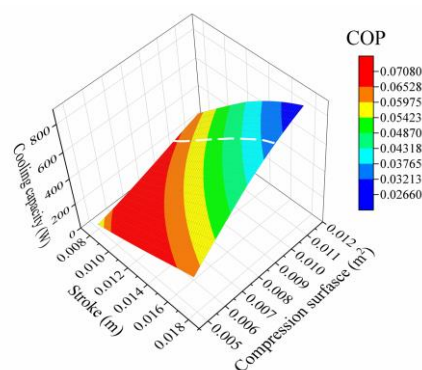


Figure 3. Influence of the parameters of piston to the cooling performance

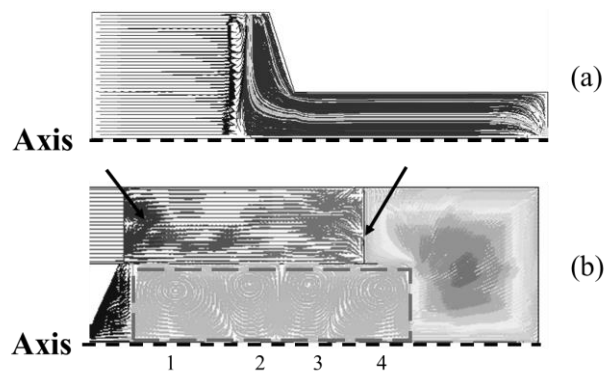


Figure 4. Transient velocity streamlines in coaxial and in-line pulse tube cold finger

3.2. The flows inside the SPTC cold finger

Figure 4 (a) and (b) show the transient velocity streamlines in both the in-line and the coaxial pulse tube cold fingers, respectively. There is more likely to be vortex inside the pulse tube in a coaxial pulse tube cold finger. As shown in figure 4 (b), the flow in the cold heat exchanger is not stable as expected. The flow at the bottom of the heat exchanger will flow straight to the wall of the heat exchanger which will bring a loss which will never exist in the in-line ones as shown in figure 4 (a). There are still four vortices inside the pulse tube which will decrease the cooling capacity by destroying the air piston. So, the flow straighter is used to make the flow steady at the inlet and outlet of the pulse tube. And the flow straighter is important to the performance of the SPTC.

3.3. Optimization of the SPTC using mixed matrices

Figure 5 (a)-(c) show the performance of the SPTC with different matrices inside. The mesh is chosen between 250-635 mesh SS screen. Both pure and mixed matrices are simulated, and the results show that the mixed matrices have higher potential than the pure matrices. In figure 5 (a), the 400-mesh and 350-mesh achieve the highest cooling capacity and COP. The cases which use other matrices get a much lower cooling capacity than the previous one. The figure 5 (b) shows the optimal cases of every mixed mesh design. The dimensional and operating parameters are the same, only the ratio of different matrices changes. The performances of the SPTC in case 1-4 are shown in figure 5 (c). Comparing the case 1-4, the case 4 gets the highest COP and cooling performance. The regenerator will be filled with mixed 400-mesh, 500-mesh and 600-mesh SS screen in the optimal case.

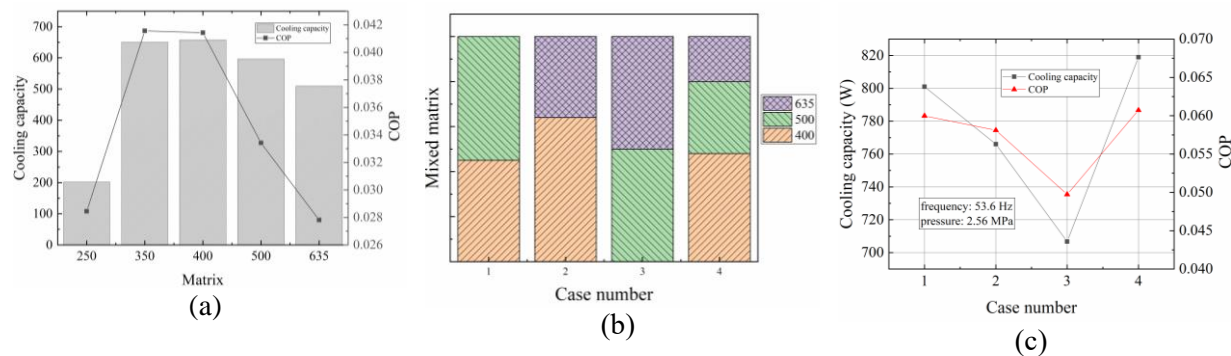


Figure 5. The cooling capacity and COP of SPTC with different matrices

3.4. The performance of the optimal case

Based on the simulation and analysis, an optimal case is figured out. The performance of this case is tested. The results are shown in figure 6. The optimal case is based on the parameters in 3.1 and the operating parameters such as the operating frequency and the charge pressure are optimized as well. Figure 6 (a) shows the performance under different status. Considering the goal cooling capacity is more than 600 W at 77 K, it can only be chosen from the points upper than the black dashed line. The yellow point is the chosen point at last. Figure 6 (b) shows the performance of the case using the chosen operating parameters. The cooling capacity and the COP will rise with the increase of the temperature of the cold head. The simulated results show that the SPTC could provide 706.4 W cooling capacity at 77 K with the input power of 13.5 kW.

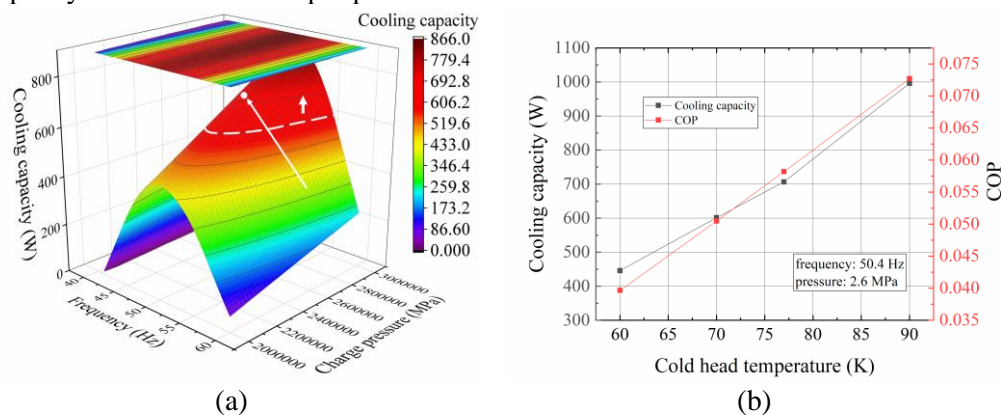


Figure 6. The cooling capacity and COP of SPTC with different frequency and pressure

3.5. The experiment and results

Figure 7 shows the experiment for the SPTC testing. The experiments consist of the SPTC, the measuring instruments, the power supply, and the PC. The test results show that the cooling capacity of the SPTC is 580 W at 77 K with the input power of 12 kW. The relative Carnot efficiency is 13%. Comparing the experimental results to the simulated ones, the cooling capacity of the SPTC does not reach the goal in the experiment. There are several reasons for this. The maximum input electric power of the compressor developed in our group is 12 kW. This limits the performance of the SPTC. Also, the heat exchanger and the flow straighter is not efficient as expected. So, the next step of our study is to improve the input electric power of the linear compressor and to optimize the heat exchanger and the flow straighter.

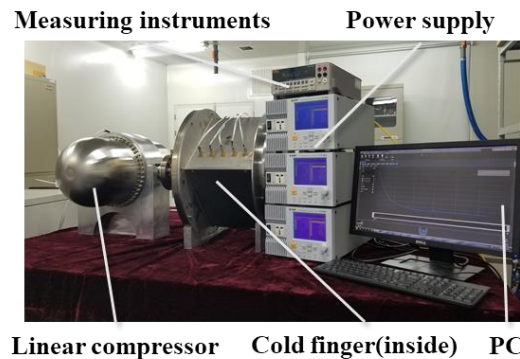


Figure 7. The experiment for the test of the SPTC

4. Conclusions

This paper presents the investigation of a single-stage Stirling-type pulse tube cryocooler targeting to provide 600W cooling power at 77K for the HTS applications. A two-dimensional model is built based on the one-dimensional simulated results to investigate the flow. The match between the linear compressor and the pulse tube cold finger is studied. The mixed matrices for high-capacity SPTC is studied. The mix of 400-mesh, 500-mesh, 635-mesh could reach the optimal performance. Both the dimensional and operating parameters are optimized. Based on the theoretical analysis, the SPTC is designed with the optimal parameters. It can provide 706.4 W at 77 K in the simulation results. In the experiment, the SPTC has a cooling capacity of 580 W at 77 K.

5. References

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Acknowledgments

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