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Effects of Design Parameters on Performance of the Stirling Refrigerator

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Abstract— **The split-type free displacer Stirling refrigerators have been widely used for the cooling of infrared sensors and HTS filters. The thermodynamic and electric performance of the Stirling refrigerator is depending on the design and operating parameters. In the Stirling refrigerator with a free displacer, the refrigeration power is a function of the pressure wave in the expansion space, dynamics of a displacer, driving frequency, and etc.. In this study, the analysis of the small Stirling refrigerator was performed to investigate the effects of design parameters on the cooling capacity. The results show the effects of charging pressure, driving frequency, cold end temperature, natural frequency of a displacer and volume of expansion space on the performance of the Stirling refrigerator.**

1. INTRODUCTION

Over the past decade and a half there has been rapid development of Stirling refrigerators, mainly for military and space application. The refrigerator working on the Stirling cycle are characterized by high efficiency, fast cool down, small size, light weight, low power consumption and high reliability.

The Stirling refrigerators have been widely used for the cooling of the infrared sensors and high temperature superconducting filters to liquid nitrogen temperature. Recently, the split-type free displacer Stirling refrigerators driven by linear compressor are used to fit requirements of a long operation lifetime[1].

A split-type free displacer Stirling refrigerator comprises a compressor and a cold finger connected by a split tube. The cold finger contains a displacer with a regenerator, a mechanical spring and an expansion space.

The thermodynamic and electric performance of the Stirling refrigerator is depending on the design and operating parameters. The typical operating parameters are the operating frequency, environmental temperature, etc..

The performance of Stirling refrigerator depends on the harmony of the dynamic characteristics of linear compressor and expander. Refrigeration power of Stirling refrigerator is the function of the pressure wave in the expansion space, dynamics of a displacer, driving frequency and etc..

The dynamic characteristics of a free displacer depend on the driving force (pressure difference between the hot and cold space, and the natural frequency of a displacer, stiffness of the mechanical springs and etc..

Koh [2] showed the characteristics of the linear compressor when the driving frequency and charging pressure change, Hong [3] showed the influence of the natural frequency of the displacer on the cooling capacity, and Park [4] did an experimental study for the phase shift between piston and displacer.

In this study, the analysis of the small Stirling refrigerator was performed to investigate the effects of design parameters (driving frequency, charging pressure, volume of expansion space and natural frequency of a displacer) on the performance of the Stirling refrigerator.

2. ANALYSIS

2.1. Modeling of Stirling refrigerator

Fig. 1 shows a typical split-type free displacer Stirling refrigerator driven by a linear compressor with the nominal cooling capacity 1 W (@80 K).

The Stirling refrigerator consists of a linear compressor, a split tube and an expander. The linear compressor has the moving coil type linear motor, two piston assembly, two buffer spaces and a compression space. The expander has a mechanical coil spring, a displacer with regenerator and an expansion space.

The pressure waves which are generated by dual opposed pistons of linear compressor are the driving force of the displacer in the expander.

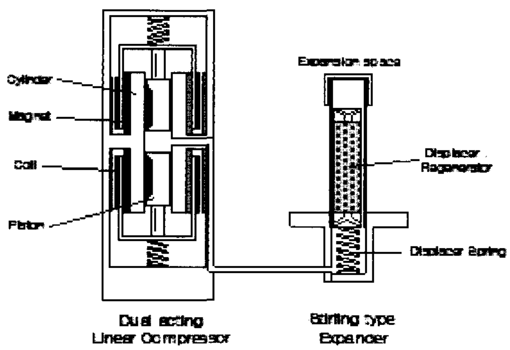

Fig. 1. Schematic diagram of the split-type free displacer Stirling refrigerator.

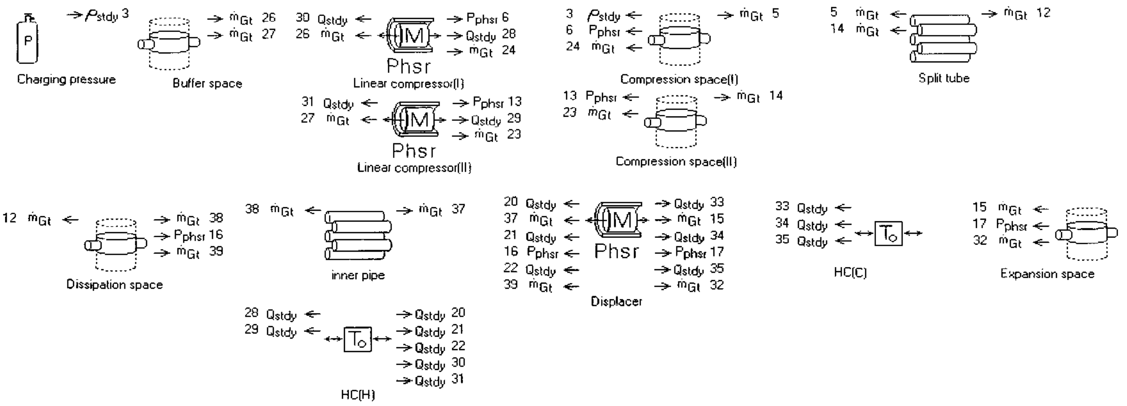

Fig. 2. Analysis model of the Stirling refrigerator

The ideal refrigeration in the expansion space is generated by the motion of the displacer and the pressure wave in the expansion space. The actual cooling capacity should be considered with radiation loss, conduction loss and etc..

The theoretical analysis of Stirling refrigerator is carried out at various levels of sophistication. The third-order analysis attempt to model energy and fluid flows of the Stirling refrigerator simultaneously [5]. Fig. 2 shows the third-order analysis model of the Stirling refrigerator in the SAGE^{TM} [6]. Variable volume space model are used for the buffer and the compression space of the linear compressor, the hot and the cold volume of the expander. The linear motor models with a spring, a damper and seal leakage are considered. A displacer and cylinder model, which has a spring, a damper, a woven screen matrix, a displacer appendix and seal leakage, is used for the displacer with a regenerator. A tube bundle model is used for the split tube. Working fluid (Helium) is assumed to be ideal gas.

2.2. Analysis conditions

Table 1 shows the specification of the split-type free displacer Stirling refrigerator. The performance of Stirling refrigerator depends on the input power. To compare the performance of refrigerator, all calculations were carried out for the given input current (I_{RMS}= 4 A). The thrust constant of the linear motor, the hot end temperature, mesh of the regenerator, the cold end temperature are kept at fixed value.

TABLE 1.
SPECFICATION OF THE STIRLING REFRIGERATOR

Specification		Value
Compressor	volume of compression space	1.4 cc
	thrust constant	6.7 N/A
	T_h	300 K
	charging pressure	20 kg_f/cm^2G [1)]
	operating frequency	50 Hz [1)]
Expander	regenerator	#250
	natural frequency of displacer	63.5 Hz [1)]
	volume of expansion space	0.17 cc [1)]
	T_c	80 K

[1)] : reference case

3. RESULTS

3.1. Effects of charging pressure and operating frequency

Fig. 3 shows the effects of the charging pressure and the operating frequency on the swept volume of the compressor piston. The swept volume of the compressor piston could be maximized at the low operating frequency and low charging pressure. At a fixed operating frequency (above 45Hz), the swept volume of the compressor piston is maximized for a specific range of charging pressure. The specific range, which could maximize the swept volume of the compressor piston, increases as the operating frequency increases. Fig. 4 shows the effects of charging pressure and operating frequency on the swept volume of the displacer. The swept volume of the displacer could be maximized at the high operating frequency and the high charging pressure. At the high charging pressure, the swept volume of a displacer increases as the operating frequency increases.

Fig. 5 shows the effects of the charging pressure and the operating frequency on the electric input power to the linear compressor. The characteristics of the electric input power of Stirling refrigerator shows the same trends of the swept volume of the compressor piston. Because the electric input power is proportional to the PV power of the compressor pistons. Around 50 Hz, the electric input power does not exceed 40 W.

Fig. 6 and Fig. 7 show the PV work at the expansion space and the cooling capacity at 80 K respectively. At a fixed operating frequency, the PV work is maximized for a specific range of charging pressure. The maximum of PV work is about 2.6 W and could be obtained at the high charging pressure and the operating frequency between 48 and 56 Hz. The cooling capacity could be estimated from the PV work at the expansion space. In the operating frequency between 51 ~ 56 Hz , above charging pressure 2.5 MPa, the cooling capacity is above 1.2 W. It is clear that the half of the PV work is used to compensate the thermal and fluid losses of the Stirling refrigerator.

To get the maximum of cooling capacity, the operating frequency should be increased as the charging pressure increases.

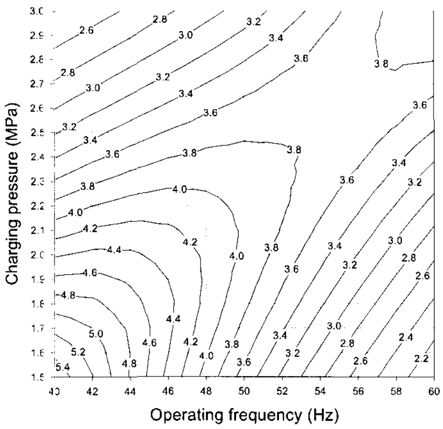

Fig. 3. The effects of charging pressure and operating frequency on the swept volume of compressor pistons (unit : cc).

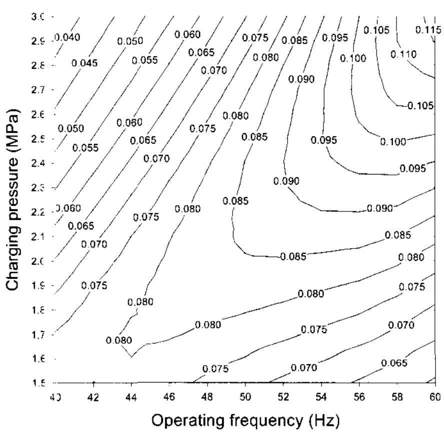

Fig. 4. The effects of charging pressure and operating frequency on the swept volume of displacer (unit : cc).

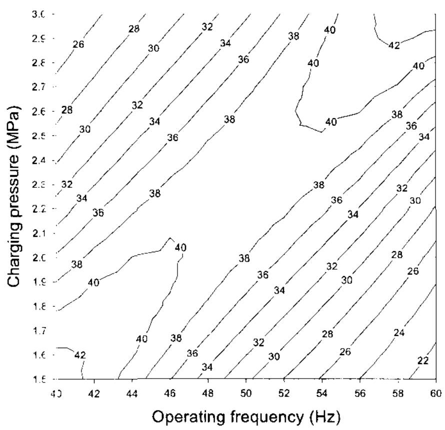

Fig. 5. The effects of charging pressure and operating frequency on the electric input power (unit : W).

Fig. 8 shows the PV work, the regenerator loss, the conduction loss and the seal loss of the displacer when the operating frequency is 50 Hz and the charging pressure is 2.06 MPa with the fixed gap width between displacer and expander. The increases of the input power results in the

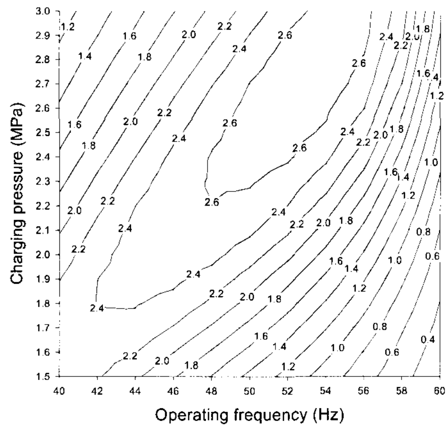

Fig. 6. The effects of charging pressure and operating frequency on the PV work of displacer (unit : W).

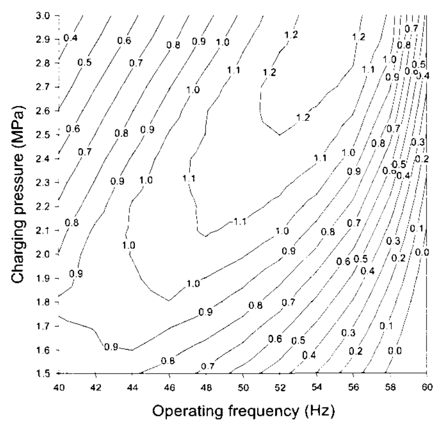

Fig. 7. The effects of charging pressure and operating frequency on the cooling capacity at 80 K (unit : W).

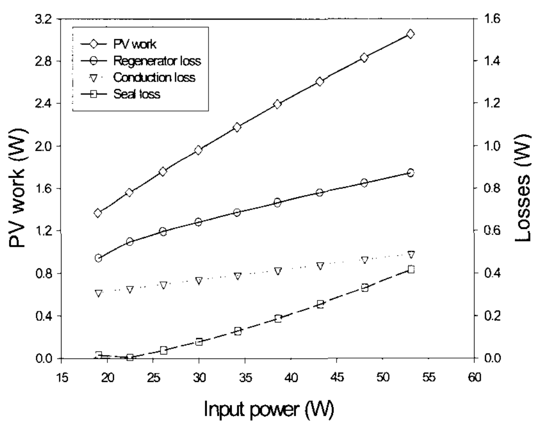

Fig. 8. PV work and losses of displacer (operating frequency : 50 Hz, charging pressure : 2.06 MPa).

increase of the swept volume of the displacer. So the PV work of the displacer increases as the input power increases. The regenerator loss increase as the swept volume of the displacer increases due to the increases of the mass flow rate through the regenerator.

Furthermore, the increase of the mass flow rate leads to the increase of the conduction loss. Hence, the conduction losses are composed of the conduction losses through the thin wall of the expander, the displacer and the meshes of the regenerator. The seal loss (enthalpy flow through the seal) has the minimum value at the small swept volume of the displacer. When the swept volume is small, the regenerator and the conduction loss is the dominant loss mechanism, but when the swept volume is large, the seal loss grows to the 80 % of the conduction loss.

3.2. Effect of cold end temperature

Fig. 9 shows the effects of the cold end temperature on the swept volume of the displacer, the cooling capacity and the COP with constant input current.

As shown as Fig. 9, the refrigerator reaches to the 40K at no load state. The swept volume of the displacer and the cooling capacity increases as the cold end temperature increase. But the % Carnot COP has a maximum value near the cold end temperature 110 K.

3.3. Effects of volume of the expansion space

Fig. 10 and Fig. 11 show the cooling capacity, the pressure amplitude in the expansion space, swept volume of the displacer and the PV diagram with the different expansion volume. The expansion volumes were adjusted by the change of the neutral position of the displacer with the fixed diameter and the length of the expander. The increase of the expansion space gives rise to the decrease of the amplitude of the pressure, the swept volume of a displacer. So the dead volume increases as the expansion volume increases. Finally, the decrease of the cooling capacity occurs. The change of the diameter of the expander results in the change of mass of the displacer. The natural frequency of a displacer is a function of the mass and the stiffness of the spring, and the natural frequency could alter the dynamic characteristics of the displacer.

Fig. 12 shows the effect of the diameter of the expander on the cooling capacity when the operating frequency is 50 Hz and the charging pressure is 2.06 MPa.

As shown in Fig. 12, the increases of the expansion space result in the decrease of the cooling capacity for the wide range of frequency ratio. The cooling capacity is rapidly decreased when operating frequency approach to the natural frequency of a displacer. The maximum of the cooling capacity is obtained when the operating frequency ratio is about 0.8.

Fig. 13 shows the influence of the charging pressure on the cooling capacity when the operating frequency is 50Hz and the frequency ratio is 0.8. The cooling capacity increases as the charging pressure increases.

The results show that the refrigerator with the larger expansion space requires the higher charging pressure to get its maximum cooling performance.

From the above results, it is clear that both of the charging pressure and the natural frequency of the displacer should be optimized to get the more cooling capacity in the larger diameter of the expander.

Table 2 shows the effect of the expansion space with the different length of the expander when the diameter of expander and the input power are fixed, the charging pressure is 3.0 MPa and the operating frequency is 50Hz. In the calculation, the displacer has the same regenerator and natural frequency, and the neutral position of the displacer is a half of the height of the expander. The results show that the cooling capacity increases as the expansion space increases. So, the increase of the expansion space by the lengthened expander is useful to the enlarging of the cooling capacity.

TABLE 2
EFFECT OF THE LENGTH OF A EXPANDER ON THE COOLING CAPACITY

Expansion space volume (cc)	Expansion space length (mm)	Cooling capacity (W)
0.201	4	1.300
0.251	6	1.357
0.301	8	1.425

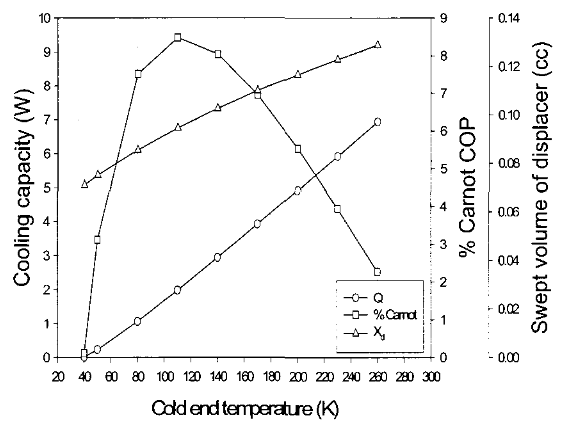

Fig. 9. Cooling capacity, swept volume of a displacer and COP (operating frequency : 50 Hz, charging pressure : 2.06 MPa)

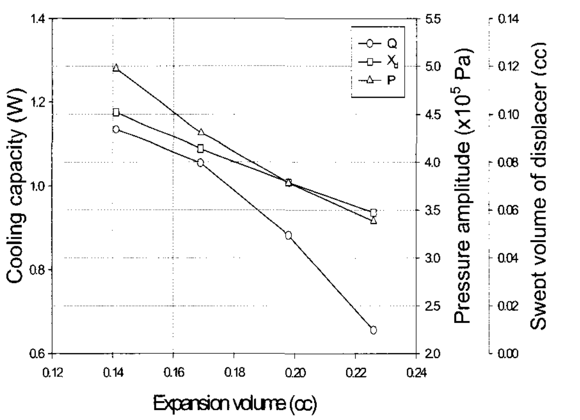

Fig. 10. Cooling capacity, pressure amplitude and swept volume of a displacer vs. expansion volume (operating frequency : 50 Hz, charging pressure : 2.06 MPa)

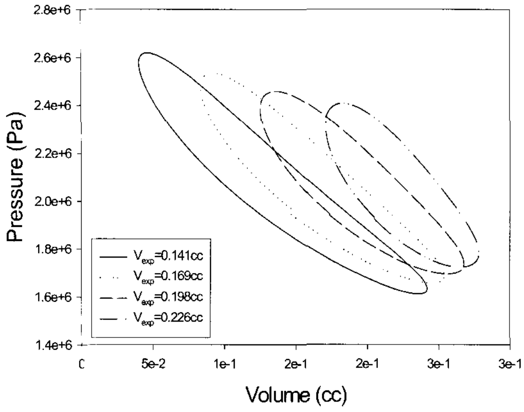

Fig. 11. PV diagram of a displacer (operating frequency : 50 Hz, charging pressure : 2.06 MPa).

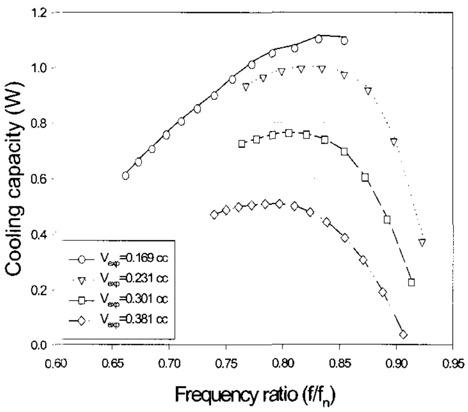

Fig. 12. Cooling capacity vs. frequency ratio of a displacer (operating frequency : 50 Hz, charging pressure : 2.06 MPa).

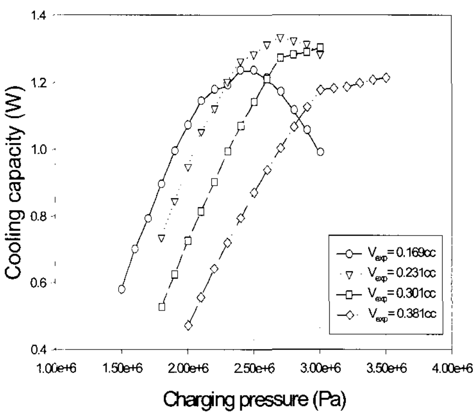

Fig. 13 Cooling capacity vs. charging pressure (operating frequency : 50 Hz)

4. SUMMARY

In this study, the analysis of the small Stirling refrigerator was performed to investigate the effects of the design parameters (driving frequency, charging pressure, volume of the expansion space and the natural frequency of the displacer) on the performance of the Stirling refrigerator.

To get the maximum of the cooling capacity, the operating frequency should be optimized with respect to the charging pressure, and the dead volume in the expansion space should be minimized.

The natural frequency of the displacer has a significant effect on the cooling capacity of the Stirling refrigerator. The maximum of the cooling capacity is obtained when the operating frequency is about frequency ratio 0.8.

The increase of the expansion space by the lengthened expander is useful to the enlarging of the cooling capacity.

ACKNOWLED GMENT

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