The effects of the clearance in the cold finger on the performance of the Stirling refrigerator

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The Stirling refrigerator has been widely used for the cooling of the infrared and cryo-sensor. The Stirling refrigerator has the clearance in the compressor and cold finger. The cooling capacity of the Stirling refrigerator comes from the relation of the pressure in the expansion space and motion of displacer. In the radial clearance of the cold finger, the parasitic dynamic losses from the leakage flow and shuttle heat losses are inevitably occurred. Therefore, to get the maximum performance of the refrigerator, the radial clearance should be optimized. In this study, the influences of the radial clearance on the performance were investigated by numerical simulation. The results show the effects of the radial clearance, operating frequency and the stroke of the displacer on the cooling performance of the Stirling refrigerator (the enthalpy flow through the regenerator and clearance, the shuttle loss).

INTRODUCTION

Over the past decade and a half there has been rapid development of the Stirling refrigerators, mainly for military and space application. The refrigerators 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 the liquid nitrogen temperature.

In the Stirling refrigerator, the clearances between the cylinder and the moving object (the piston or the displacer) are inevitably occurred. The clearance between the cylinder and piston in the compressor has the effects on the performance and reliability of the compressor, and the clearance between the displacer and the cylinder in the cold finger has the significant effects on the thermal performance of the refrigerator.

The gross refrigeration of the Stirling refrigerator comes from the relation of the pressure in the expansion space and motion of displacer. The reduction in the amplitude of pressure would result from the excessive leakage flow through the clearance in the cold finger. It is well known that a conventional refrigerator with displacers usually uses seal rings to reduce the leakage flow. The cooling capacity can be calculated by subtracting all the loss terms from gross refrigeration. The clearance would lead to the parasitic dynamic losses. The axial temperature gradient along the expander causes the shuttle heat loss[1,2]. The repetitive filling and emptying of the clearance cause the appendix loss[3].

In this study, the effects of the clearance in the cold finger on the cooling performance of the Stirling refrigerator were investigated by analysis.

DESCRIPTION OF ANALYSIS

A Stirling refrigerator comprises of a compressor and a cold finger connected by a tube. The cold finger contains a displacer with regenerator and an expansion space as shown Figure 1.

The displacer with regenerator is actuated by the mechanical driving mechanism. For the purpose of providing a refrigerator with regenerator with displacer having a good cooling performance, the seal rings

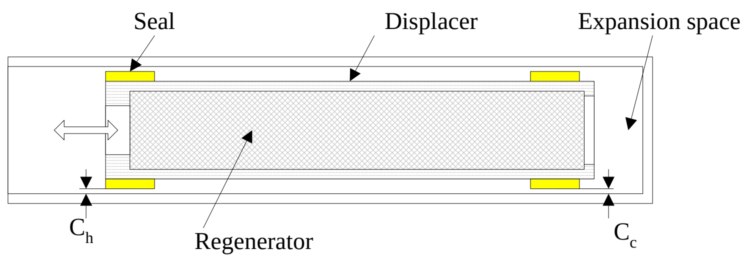


Figure 1 The schematic diagram of a cold finger of the Stirling refrigerator

are employed at the hot and cold end of the displacer.

Table 1 shows the specifications of the Stirling refrigerator in the calculation. The SAGE[4] was used to investigate the effects of the operating frequency, the stroke of the displacer and the radial clearance between the seal rings and the expander on the cooling performance.

Table 1 The specifications of the refrigerator

Working fluid	Helium (real gas)	Piston/Displacer phase	90 deg
Charging pressure	2.2 MPa	Regenerator	#250 (Porosity 0.69)
Piston diameter	10 mm	Regenerator diameter	7.1 mm
Stroke of piston	4 mm	Regenerator length	70 mm
Expander diameter	8 / 7.7 mm	Hot temperature	300 K
Displacer diameter	7.4 / 7.1 mm	Cold temperature	80 K

Table 2 shows the calculation results for the operating frequency of 50 Hz, the stroke of the displacer of 3 mm and the radial clearance between the seal rings and the expander of 0.015 mm. The result shows the enthalpy flow through the refrigerator is a dominant heat loss. The losses by the clearance amount to the 33% of the total loss. The conduction loss through the wall of the expander and displacer is relative small. Figure 2 shows the PV diagram of the compression space and the expansion space.

Figure 3 shows the mass flow rate flowing to the expansion space. The flow through the clearance has a phase lag of 80 degree to the flow through the regenerator and small amplitude.

Table 2 The calculation results

PV work in compression space	21.33 W
Gross refrigeration	3.557 W
Enthalpy flow through the regenerator	1.162 W
Enthalpy flow through the clearance	0.1744 W
Shuttle heat loss	0.5314 W
Conduction heat loss	0.2732 W
Cooling capacity	1.416 W

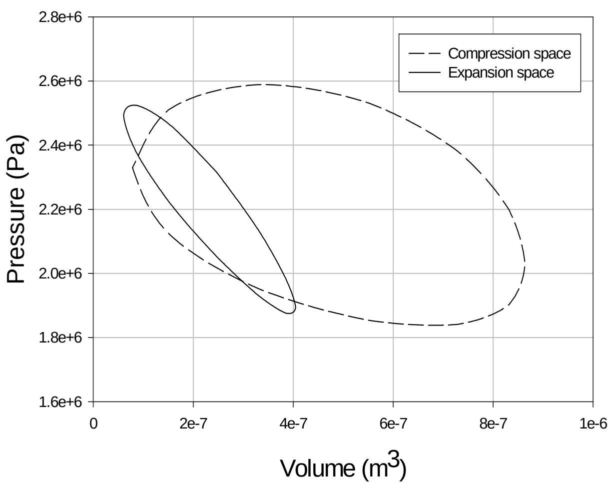


Figure 2 PV diagram in the compression and expansion space

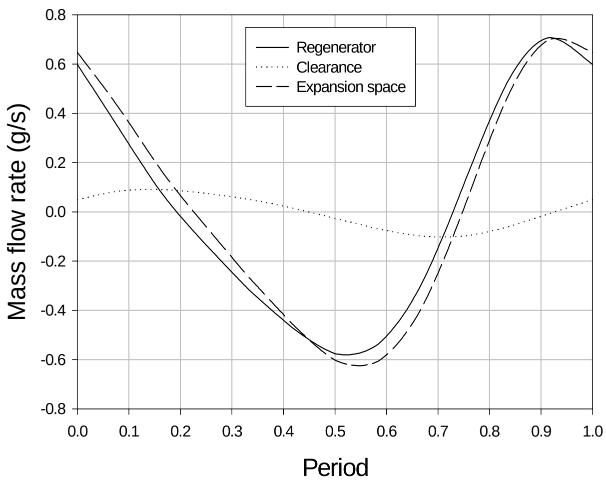


Figure 3 mass flow rate flowing to the expansion space

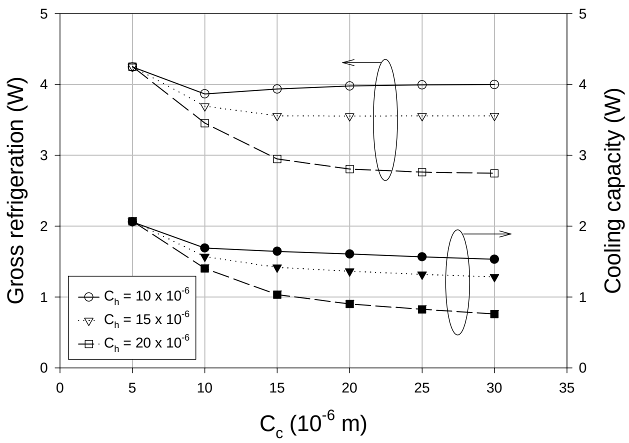
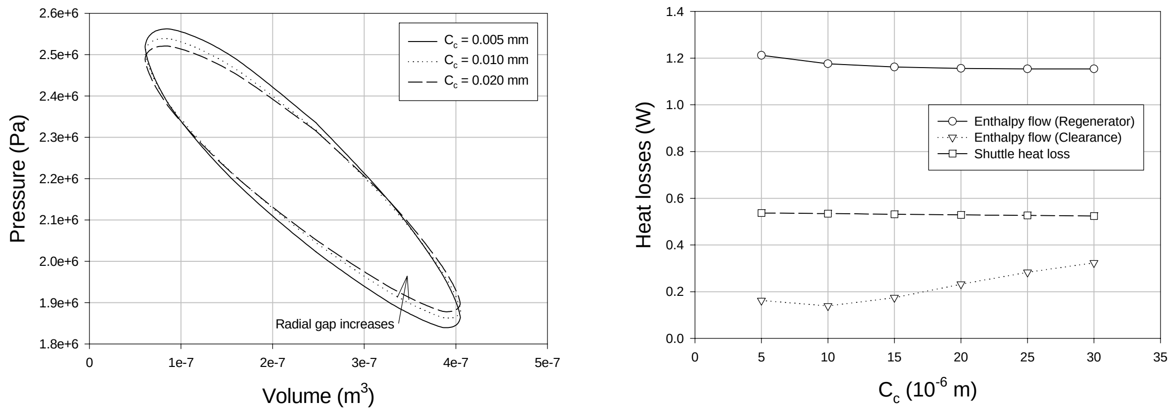


Figure 4 Gross refrigeration and cooling capacity vs. radial clearance

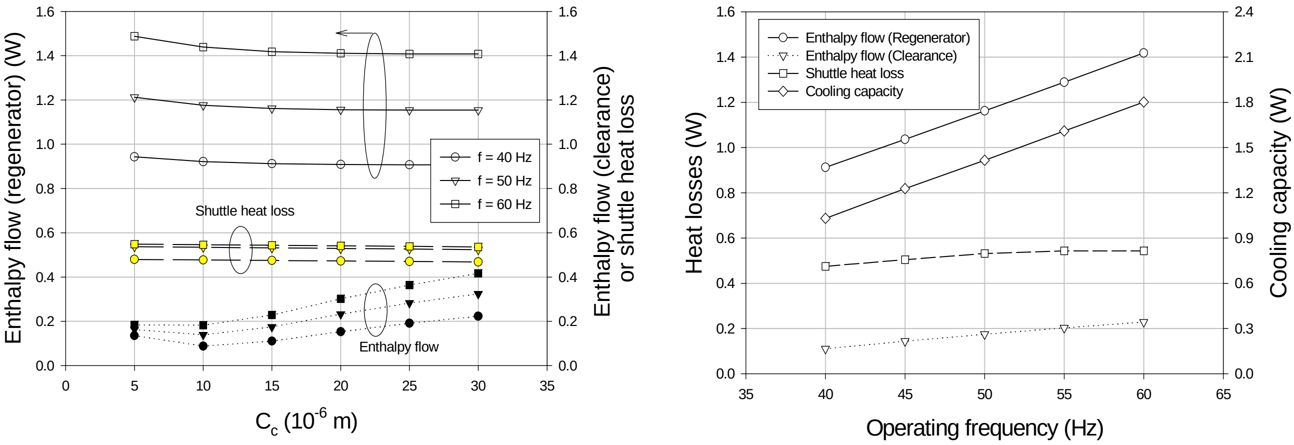


(a) PV diagram (b) heat losses

Figure 5 PV diagram and heat losses vs. radial clearance of cold end

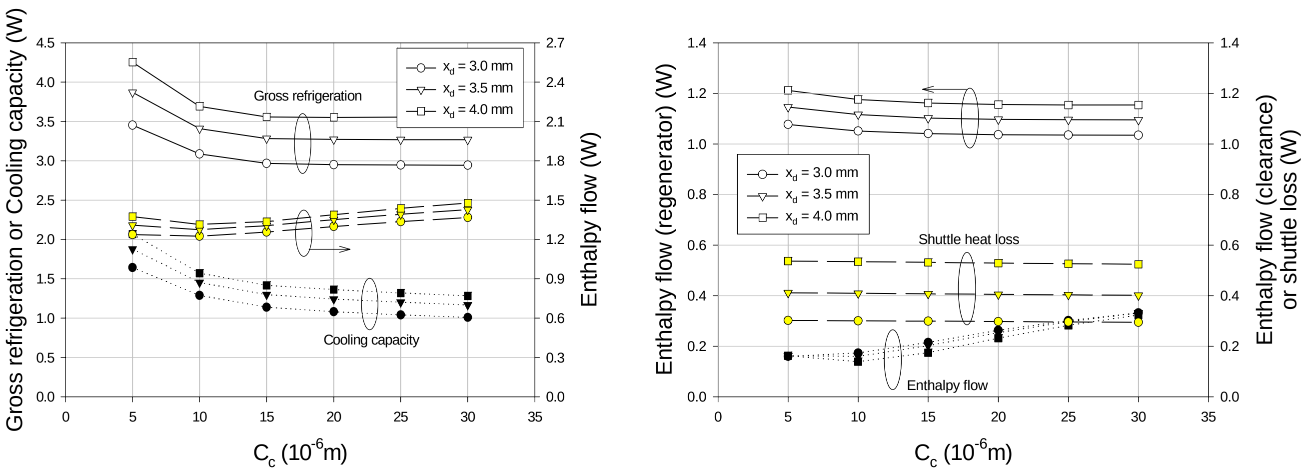
Figure 4 show the calculation results of gross refrigeration and cooling capacity when the radial clearances of hot end (C_h) are 0.01, 0.015, 0.02 mm as function of different radial clearance of cold end (C_c). The results show the cooling capacity is maximized when the C_c is small. The cooling capacity decreases as the C_c increases. At the given C_c, the gross refrigeration and cooling capacity increase as the C_h decreases. The influence of the C_h on the cooling capacity is small when the C_c has a small value.

Figure 5 show the PV diagram of expansion space, the enthalpy flow through the regenerator and the losses from clearance when the the C_h is 0.015 mm as a function of the C_c. It is obvious that the larger C_c result in the smaller amplitude of pressure in the expansion space due to the leakage flow through the clearance. The enthalpy flow through the regenerator decreases as the C_c increases, whereas the enthalpy flow through the clearance increases. So the increase of the enthalpy flow through the clearance leads to the decrease of the cooling capacity when the C_c increases.



(a) heat losses (C_h = 0.015 mm) (b) $C_h = C_c$ = 0.015 mm

Figure 6 The cooling performance of the refrigerator with different operating frequency



(a) Gross refrigeration & cooling capacity (b) heat losses

Figure 7 The cooling performance of the refrigerator with different stroke

Figure 6 show the cooling performance of the refrigerator with different operating frequency(f) and C_c when the stroke of the displacer is 4 mm and the C_h is 0.015 mm. As shown as Figure 6, the enthalpy flow through the regenerator is proportional to the operating frequency. The enthalpy flow through the clearance doe not have a great role in the losses when the operating frequency is low and C_c is small.

Figure 7 show the cooling performance of the refrigerator with different stroke of displacer(x_d) and C_c when the operating frequency is 50 Hz and the C_h is 0.015 mm. At the high x_d, the increases of the cooling capacity are relative small than the increases of the gross refrigeration due to the larger shuttle heat loss. As shown as Figure 7, when x_d is small and C_c is large, the amount of the enthalpy flow through the clearance exceed the shuttle loss.

It is clear that the enthalpy flow through the clearance depends on the operating frequency and the radial clearance of the cold end, whereas the shuttle loss depends on the stroke of the displacer. The leakage flow through the clearance has the effects on the cooling capacity through the gross refrigeration and the enthalpy flow.

SUMMARY

In this study, the effects of the clearance in the cold finger on the cooling performance of the Stirling refrigerator were investigated by analysis. The SAGE was used to investigate the effects of the operating frequency, the stroke of the displacer and the radial clearance between the seal rings and the expander on the cooling performance. The calculation results show that the enthalpy flow through the refrigerator is a dominant heat loss. The leakage flow through the clearance has the effects on the cooling capacity through the gross refrigeration, the enthalpy flow and the shuttle heat loss. The enthalpy flow through the clearance depends on the operating frequency and the radial clearance of the cold end, whereas the shuttle loss depends on the stroke of the displacer.

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