Optimization Design and Experimental Study on a 2.8W at 80K Stirling Cryocooler Regenerator

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ABSTRACT

The regenerator is the key to high efficiency operation of a Stirling cryocooler. In this paper, the regenerator of a 2.8W@80K Stirling cryocooler was optimally designed. The regenerator length, the pressure ratio at the cold end, and the mesh number of the matrix wass optimized using REGEN 3.3. Experiments were carried out and it was found that the efficiency of the regenerator can be improved by changing the mesh parameters and the packing form of the matrix. What is more, using the same mesh number, a mesh of thinner diameter stainless steel wires can further improve the efficiency of the regenerator.

INTRODUCTION

The regenerator is the key component of a Stirling cryocooler, its heat transfer process includes two stages; the hot blow period and the cold blow period. During the hot blow period, hot gas goes through the regenerator, after heating the matrix, its temperature decreases; while in the cold blow period, cold gas goes through the regenerator in the opposite direction, after cooling the matrix, its temperature increases. One hot blow period and one cold blow period make up a heat transfer cycle. Inside the regenerator, both flow and heat transfer between the matrix and the gas are alternating processes. The efficiency of the regenerator is the main factor restricting the efficiency of a Stirling cryocooler. At present, the efficiency of the regenerator is generally 7-9%. Many theoretical analyses and experimental results show that the regenerative loss and the pressure drop loss are the main factors affecting the performance of a regenerator [1-3]. The methods of improving the regenerative loss conflicts with methods to improve the pressure drop loss. In order to improve the regenerative efficiency, the heat transfer area should be increased, which will also increase the flow resistance in the regenerator, thus the pressure drop loss is increased. The focus of optimizing the regenerator is minimization of the sum of the two losses. In this paper, based on the Enthalpy Flow Modulating Phase Theory [4, 5], the optimal design of a 2.8W@80K Stirling cryocooler regenerator was achieved. The regenerator length, pressure ratio at the cold end, mesh number of matrix, packing form of the matrix in the regenerator was optimally designed, respectively, and an experimental verification was also carried out.

THEORETICAL MODEL OF REGENERATOR [6, 7]

The regenerator is a cylindrical tube filled with a porous media. Helium gas flows through the void volume. The model is based on a one-dimensional flow equation of helium gas and thermal equilibrium equations of matrix materials to obtain numerical solutions. In the model, both the pressure drop of the helium flowing through the porous media and the heat transfer between the gas and the matrix are modified. The model assumes that the pressure wave and the mass flow rate in the regenerator oscillate sinusoidally. The temperature gradient in the axial direction of the regenerator is greater than 200 K. The model is as shown in Figure 1.

When the regenerator is working, the direction of the heat transfer between the matrix and the gas alternates each half cycle. Figure 2 shows how the temperature amplitude of a thermal wave decays as it travels within a solid medium. The distance where the temperature amplitude is 1/e of the surface is defined as the solid's thermal penetration depth δ_t, that is

$$\delta_t = \sqrt{\frac{2k}{\omega \rho c_p}} \tag{1}$$

For efficient heat exchange in a regenerator, two conditions have to be satisfied:

(1) The characteristic dimension of the matrix should be smaller than the thermal penetration of the matrix material $\delta_{t,m}$, so that the heat capacity of the matrix material is fully used.

(2) The hydraulic diameter of the flow channel should be smaller than the thermal penetration of the working fluid $\delta_{t,m}$ to provide sufficient heat exchange with the fluid.

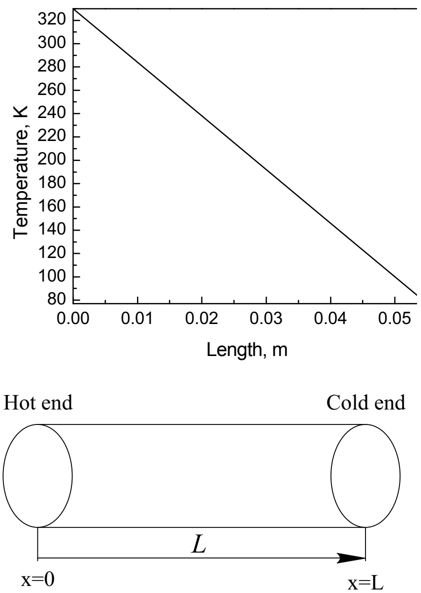

Figure 1. Model of regenerator

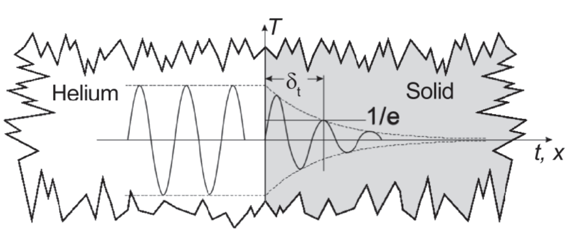

Figure 2. The decay of temperature amplitude inside a solid

Table 1. Parameters of stainless steel

Mesh number	Wire diameter / μm	Porosity	Hydraulic diameter / μm
200	50	0.690788	111.7
250	40	0.688951	88.6
300	35	0.6766	73.23
325	35	0.647578	64.31
350	35	0.620842	57.31
400	30	0.628946	50.85
320	28	0.718062	71.31
340	24	0.7552	74.04

Table 1 shows the parameters of stainless steel mesh. Figure 3 shows the heat penetration of stainless steel $\delta_{t,m}$ as a function of the temperature and the diameter of the stainless steel wire for frequencies from 60 Hz to 300 Hz. From Figure 3, we can see that when the 80K Stirling cryocooler regenerator is in the hot blow period, the diameter of the matrix (stainless steel wire mesh) is smaller than the thermal penetration depth $\delta_{t,m}$ of the matrix. The first requirement is satisfied.

Figure 4 shows the relationship between the thermal penetration depth of the helium and the matrix hydraulic diameter of the openings in the screen mesh. The regenerative loss comes mainly from the process of heat transferring from the matrix to the helium, especially at cryogenic temperatures. In Figure 4, when the temperature of the regenerator is less than 80K, the hydraulic diameter of the flow channel is close to or even bigger than thermal penetration depth $\delta_{t,m}$ of the gas, it doesn't meet the second condition.

One factor affecting the efficiency of the regenerator is that in the cold blow period, when the heat is transferred from the matrix wire mesh to the helium at the cold end, the heat can't permeate to the center of helium fully, some helium doesn't participate in this heat transfer process, so it increases the axial heat conduction loss of helium. Therefore, the main way to increase the efficiency of regenerator is to increase the heat transfer performance between matrix and helium at the cold end during the clod blow period.

THE OPTIMIZATION RESULTS AND EXPERIMENTAL STUDY

Optimization of a Regenerator's Length

REGEN3.3 was used to optimize the length of a 300 mesh stainless steel regenerator for a given mass flow rate and flow area at the cold end. As seen in Figure 5, the x-axis means regenerator's length, and Y-axis means COP. It is seen that COP has the optimum value when the regenerator's length is 55mm.

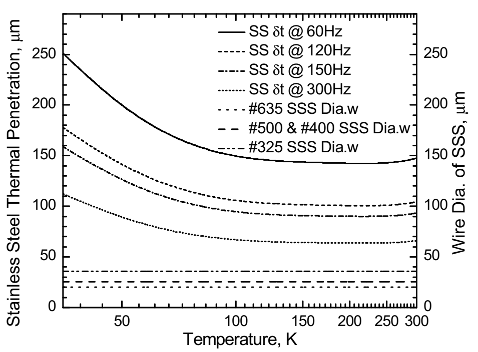

Figure 3. Thermal penetration depth of stainless steel at varied frequencies in comparison to the wire diameters of typical SSS.

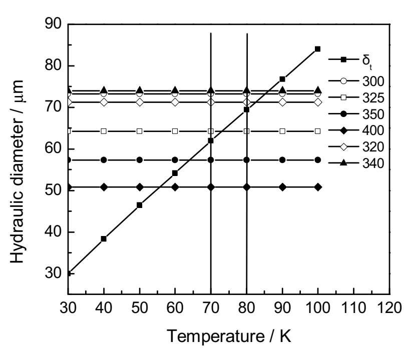

Figure 4. Hydraulic diameter and heat penetration.

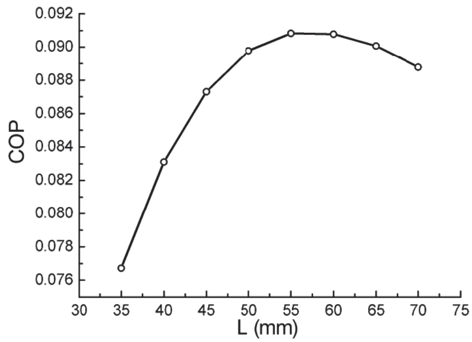

Figure 5. COP changes with length

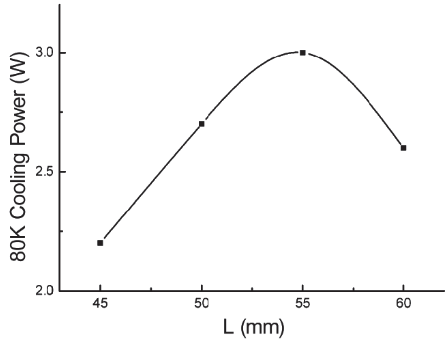

Figure 6. Experiment results of different lengths

In the experiments, we used four different lengths of regenerators in the same Stirling cryocooler. The results are shown in Figure 6 which agrees well with the theoretical calculations. So, for the 2.8W@80K Stirling cryocooler regenerator, we can use the optimal calculation for the length of regenerator.

Effect of Cold End Pressure Ratio

Figure 7 shows the relationships of 'the flow area/mass flow rate at cold end' and COP for different cold end pressure ratios. It is seen that the COP in every cold end pressure ratio has its own peak value, and the peak value increases with the cold end pressure ratio. So, the most direct way to increase the efficiency of Stirling cryocooler is to decrease the pressure loss of helium when it flows through regenerator, to increase the cold end pressure ratio, thus the efficiency of regenerator can be increased.

Effect of Mesh Numbers of Matrix

Figure 8 shows the COP curves a function of "the flow area/mass flow rate of cold end" for different size regenerator meshes. It is seen in Figure 8 that for the Stirling cryocooler, the COP for 400 mesh is the highest. In our experiments, the results show that a COP of the 325 mesh is the highest. The reason for the difference between the model and measured results is that when we used a higher mesh number, the other parameters in the Stirling cryocooler changed. For example, the flow resistance of the 400 mesh matrix is larger, which leads to a smaller cold end pressure ratio. In the model, we assume that the cold end pressure ratio of the regenerator is the same and the theoretical calculation deviates from the experiment results.

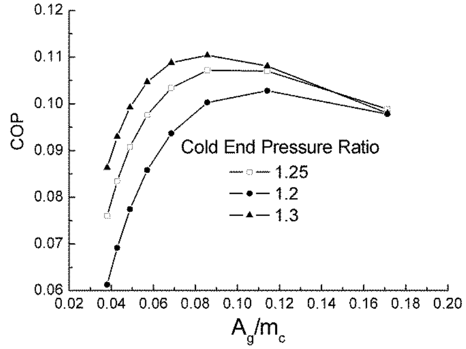

Figure 7. COPs for different cold end pressure ratio

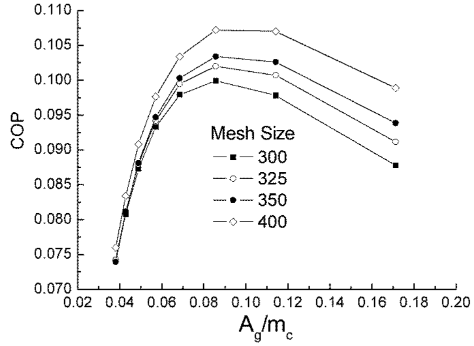

Figure 8. COPs for different matrixes

Effect of Packing Form of the Matrix

When analyzing different mesh numbers of the matrix above, we know that the fill rate of the matrix may influence the efficiency of the Stirling cryocooler. This paper also studies the different packing forms of the matrix in the regenerator, including the theoretical calculations and experiments for mixed matrix fillings and using thinner wire diameters with the same mesh number.

Table 2 shows the corresponding hydraulic diameters for fill rates of different stainless steel wire meshes. In Table 2, it can be seen that for a mesh number of 340 when the fill rate varies from 0.76 to 0.70, the hydraulic diameter of helium decreases from 74 µm to 56 µm for a temperature range of 70 K to 80 K, as shown in Figure 9. Using a smaller wire diameter stainless steel wire, and choosing the right the packing form for the mesh, the hydraulic diameter of the matrix can be reduced to meet the heat penetration condition; the second condition.

Figure 10 shows the performance curves of different fill rates. The COP of stainless steel wire mesh whose wire diameter is 24 µm or 28 µm is better than those with a wire diameter of 35 µm.

Table 2. Parameters of different matrixes in realistic fill rate

Mesh number	Wire diameter/um	Bore diameter/um	wire+bore diameters/um	Void ratio	Hydraulic diameter/um
300	35	50	85	0.6766	73.23
325	35	43	78	0.647578	64.31
400	30	33.5	63.5	0.628946	50.85
320	28	50	78	0.718062	71.31
320	28	50	78	0.68	59.5
340	24	53	77	0.7552	74.04
340	24	53	77	0.68	51
340	24	53	77	0.7	56

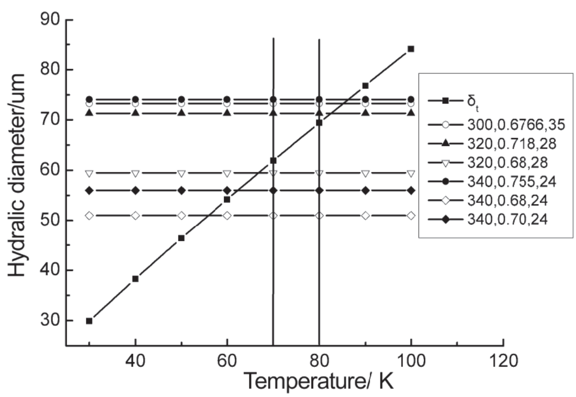

Figure 9. The corresponding hydraulic diameters and heat penetrations in realistic fill rate

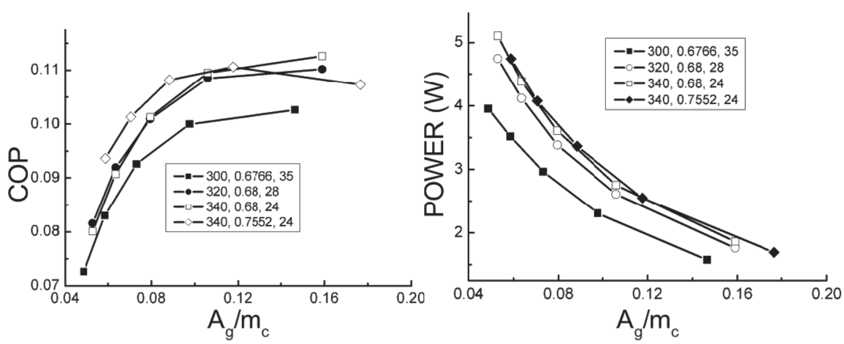

Figure 10. COPs and power curves for different matrixes

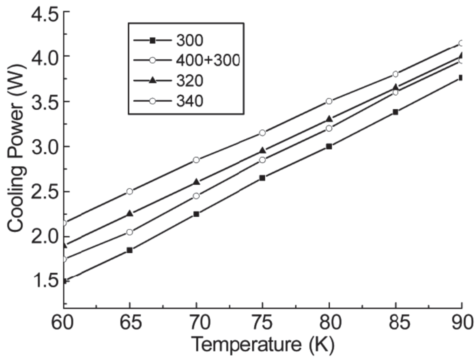

Figure 11. Experiment results in different packing forms

Guided by the theoretical calculation results in this paper, we used 300 mesh, 400+300 mesh, 320 mesh, and 340 mesh stainless steel wire mesh in the experiments, respectively.

Figure 11 shows the experimental results of four different packing forms, "400+300" indicates that the regenerator included the 400 mesh stainless steel screen in the cold end. In Figure 11, the refrigeration capacity of 400+300 mesh is 0.2 W larger than 300 mesh in the temperature range of 80 K. The reason is that the wire diameter of 400 mesh is smaller so that in the cold blow period, the hydraulic diameter is smaller than the thermal penetration depth $\delta_{t,m}$ of helium. This increases the heat exchange ability of helium. However, it is not good to fill too much 400 mesh stainless steel into the cold end, because it will increase the flow resistance by too much. This increases the pressure drop loss of helium flowing through regenerator, and decreases the pressure ratio at the cold end, which decreases the refrigeration performance.

CONCLUSIONS

This paper achieved an optimal design and experimentation of a 2.8W@80K Stirling cryocooler regenerator, using REGEN 3.3 to design the regenerator's length, pressure ratio at the cold end, mesh number of the matrix, the packing form of the matrix in the regenerator, respectively, and verifies through experiments. Theoretical and experimental analysis shows:

- The main factor affecting the efficiency of the 2.8W@80K Stirling cryocooler inadequate heat transfer of helium at the cold end.
- We can use wire mesh of different mesh numbers at different axial regenerator temperature ranges to increase the efficiency of regenerator.
- When the mesh number is the same, using a smaller wire diameter stainless steel mesh can increase the efficiency of regenerator.

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