Numerical Simulation of a Regenerator in a Two-Stage Pulse Tube Refrigerator

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ABSTRACT

A two-stage pulse tube refrigerator (PTR) is the simplest version of a multistage PTR and is also the most commonly used version. The second regenerator is one of the key components in its design. Through a series of simulation by using REGEN 3.2, the cold end temperature is optimized for a second stage regenerator with PV work of 1 W at the cold end, a hot end temperature from 50 to 100 K, the regenerator diameter of 8.9 mm, the operating frequency from 30 Hz to 60 Hz, and temperature of cold end of 20 K or 30 K. The effects of three different matrix materials: stainless screen mesh no. 400, stainless screen mesh no. 500 and lead spheres are discussed.

INTRODUCTION

Pulse tube refrigerators have demonstrated many advantages with respect to temperature stability, vibration, reliability and lifetime among small cryocoolers. It is easier to achieve a cold end temperature below 20K for a two-stage high frequency pulse tube refrigerator than that of one-stage.[1] The second stage regenerator is one of the key components. Program REGEN 3.2[2] developed at NIST is a very useful tool to simulate the performance of the regenerator for a pulse tube refrigerator.

MODEL DESCRIPTION

The REGEN 3.2 model, developed by Gray and Radebaugh[2], is based on a numerical solution of a one-dimensional equation for the flow of the helium gas through a porous matrix with an additional thermal conservation equation for the matrix temperature. Besides the parameters defining the matrix material and the regenerator, the gas temperature at the inflow of the cold end and the hot end, the frequency and phase difference, the initial pressure is necessary. Three other parameters, the pressure ratio, the phase angle between the mass flow and the pressure wave at the cold end, can be specified as an alternate.

The net refrigeration power (Qc) is one of the important parameters describing performance of the regenerator:

$$Qc=GRCADJ-RGLOSS-HTFLUX \tag{1}$$

where RGLOSS is the loss due to the regenerator ineffectiveness, and HTFLUX is the heat flux due to thermal conduction through the cold side of the matrix

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COP is net refrigeration power normalized by the PV work at the hot end:

$$COP = Qc / PVWK0T \tag{2}$$

The regenerator operates with a charge pressure of 3 MPa, the temperature of hot end from 50 to 100 K, and a cold end temperature from 10 to 30 K. The effects of the geometry of the regenerator are achieved. The commonly used stainless screen steel matrix is not suitable when the cold end temperature is below 20K, so different material is used to improve the performance of the regenerator. The results of the simulation show that lead sphere is helpful to get a lower cold end temperature and a higher COP.

RESULTS AND DISCUSSION

Effect of Length of Regenerator

The length of regenerator is optimized. The matrix material is stainless screen mesh no. 500. The effect of the length of regenerator is shown in Figure 1. The optimized length range of regenerator is from the 0.060 m to 0.065 m. The effect of the working frequency is as shown in Figure 2. It can be concluded the optimized lengths vary little with the working frequency.

Effect of Hot End Temperature

Besides the geometry of regenerator, the matrix material is important to get an efficient regenerator. Three matrix materials are discussed. Materials numbered 1, 2, 3 are, respectively, the regenerators with lead sphere, stainless screen mesh no. 400 and stainless screen mesh no. 500. The effect of hot end temperatures on COP and net refrigeration power is shown in Figure 3 and Figure 4. The net refrigeration power of regenerator 1 is the highest, and it becomes higher with a decrease in the hot end temperature. The gross refrigeration powers of regenerator 2 and regenerator 3 are almost the same; however, because the difference in the matrix structure, the regenerator losses of regenerator 3 are lower than that of regenerator 2. The net refrigeration power of regenerator 3 is higher than that of regenerator 2.

Effect of Cold End Temperature

One of the targets to study two-stage pulse tube refrigerator is to obtain the lowest cold end temperature . From the above-mentioned simulation, stainless screen mesh no. 500 and lead sphere are chosen for analysis. By decreasing the cold end temperature , the effect of the stainless screen mesh no. 500 and lead sphere is seen. The effect of cold end temperature is shown in Figure 5 and Figure 6. When the temperature is below 15 K, the COP of regenerator 1 is higher than the COP of regenerator 3. It is concluded that the lead sphere is better when the temperature of cold end is below 15 K.

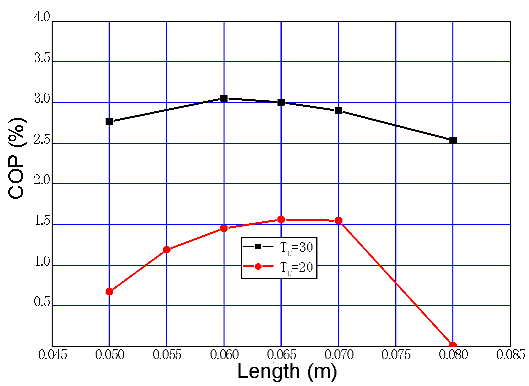

Figure 1. COP as function of length of regenerator for fixed frequency, area, PV1, hot end temperature.(f=50 Hz, PV1=1 W, T_H=100 K, D=8.9 mm)

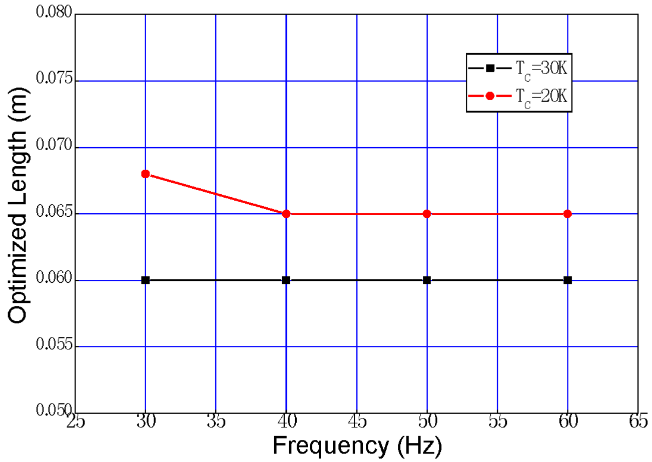

Figure 2. Optimized length of regenerator as function of frequency. (PV1 = 1 W, T_H = 100 K, D = 8.9 mm)

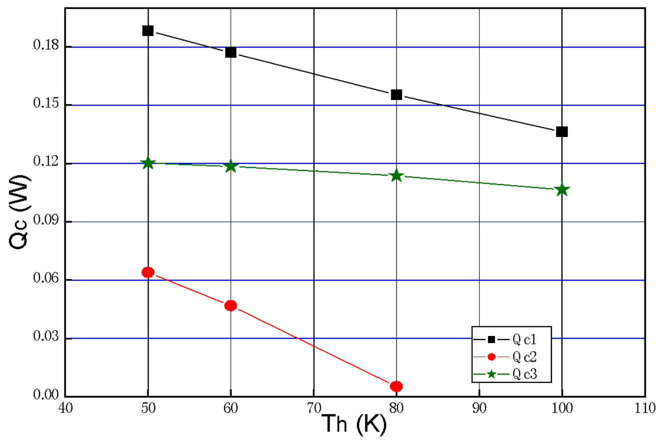

Figure 3. Net refrigeration power as function of hot end temperature. (T_c = 20 K, L = 60 mm, D = 8.9 mm)

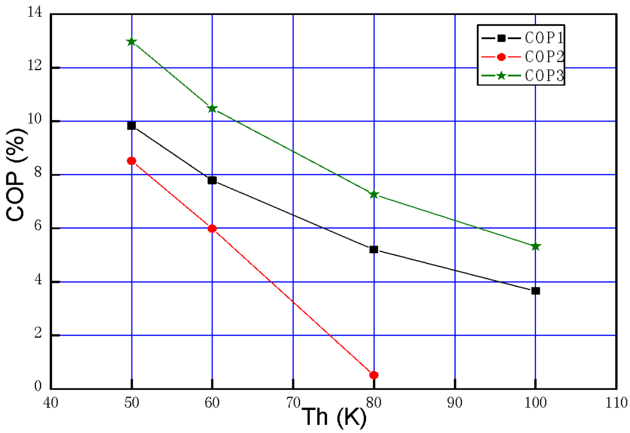

Figure 4. COP as function of hot end temperature for fixed volume rate of cold end. (T =20 K, L=60 mm, D=8.9 mm)

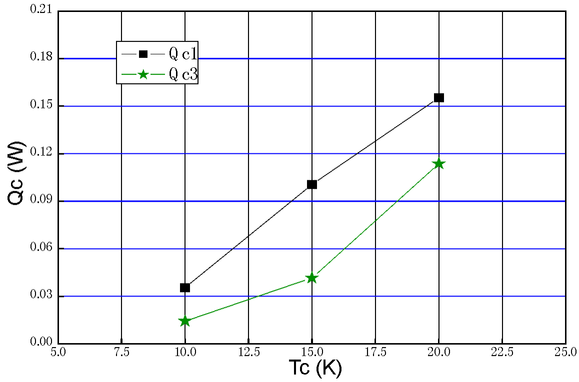

Figure 5. Net refrigeration power as function of cold end temperature for fixed volume rate of cold end. (T_H=80 K, L=60 mm, D=8.9 mm)

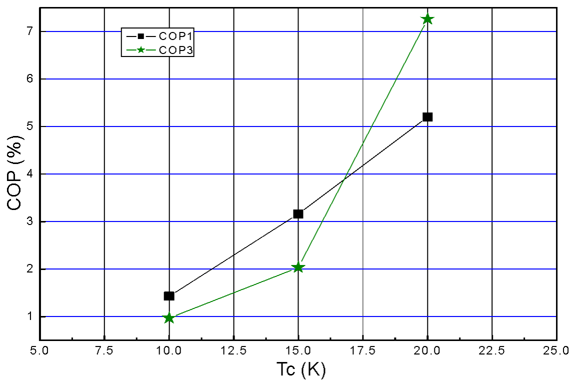

Figure 6. COP as function of cold end temperature for fixed volume rate of cold end. (T_H=80 K, L=60 mm, D=8.9 mm)

Effect of Lead Sphere Diameter

Figure 7 and Figure 8 show the effects of diameter of lead sphere. It can be concluded that if the diameter of lead sphere is not small enough, performance of the regenerator will be bad.

CONCLUSION

Through a serial of simulation using REGEN 3.2, some useful rules are revealed. For the second stage regenerator, when PV work power is 1 W, temperature of hot end is 100 K, regenerator diameter is 8.9 mm, the frequency between 30 Hz to 60 Hz, temperature of cold end 20K or 30K, the optimized length is between 0.060 m to 0.065 m, which varies little with the frequency. When the temperature of cold end is 20K, net refrigeration power of the regenerator with lead sphere is higher, and COP with stainless screen mesh no. 500 is higher. If the temperature of the cold end is below 15 K, both the COP, and the refrigeration power of the regenerator with lead sphere are higher than others. To be sure that the second stage regenerator works well under very low temperature of the cold end, the diameter of lead sphere must be smaller than 0.09 mm.

ACKNOWLEDGMENT

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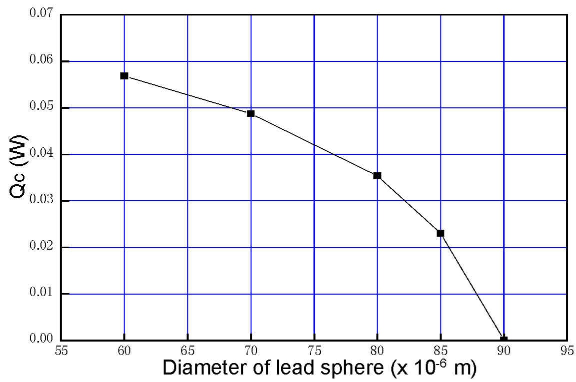

Figure 7. Net refrigeration power as function of diameter of lead sphere for fixed mass rate of cold end. (T_H=80 K, Tc=10 K, L=60 mm, D=8.9 mm)

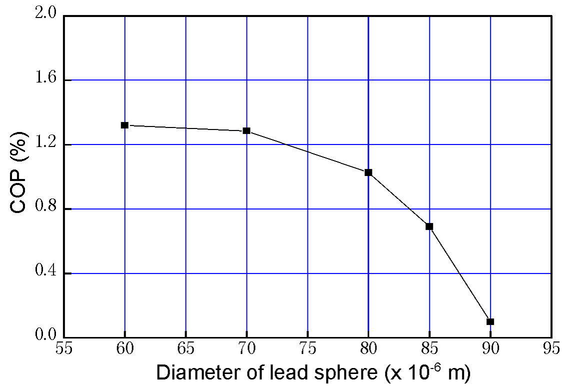

Figure 8. COP as function of diameter of lead sphere for fixed mass rate of cold end. (T_H=80 K, Tc=10 K, L=60 mm, D=8.9 mm)

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