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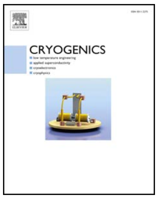

Research paper

An efficient miniature 120 Hz pulse tube cryocooler using high porosity regenerator material

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ABSTRACT

A 1.22 kg coaxial miniature pulse tube cryocooler (MPTC) has been fabricated and tested in our laboratory to provide cooling for cryogenic applications demanding compactness, low mass and rapid cooling rate. The geometrical parameters of regenerator, pulse tube and phase shifter are optimized. The investigation demonstrates that using higher mesh number and thinner wire diameter of stainless steel screen (SSS) can promote the coefficient of performance (COP) when the MPTC operates at 120 Hz. In this study, the 604 mesh SSS with 17 μm diameter of mesh wire is constructed as filler of regenerator. The experimental results show the MPTC operating at 120 Hz achieves a no-load temperature of 53.5 K with 3.8 MPa charging pressure, and gets a cooling power of 2 W at 80 K with 55 W input electric power which has a relative Carnot efficiency of 9.68%.

1. Introduction

Over the past decades, pulse tube cryocoolers (PTCs) have been widely used in space and military applications with its inherent merits, such as high reliability, low cost and low mechanical vibration [1,2]. In recent years, many research institutes and companies have paid more attention to developing the MPTCs with the characteristics of compactness, low mass and rapid cooling rate. Meanwhile, lots of papers referring to theory and applications of MPTCs have been published and discussed [3–7].

In the previous papers regarding the MPTCs [8–10], the mechanical geometrical size of PTCs was just simply reduced and the operating parameters were generally characteristic of the conventional scale PTCs. However, the corresponding efficiency of MPTCs is not as high as classical PTCs. The comprehensive understanding of reducing scale impacts was the key component to miniaturize the PTCs, because the reduction would limit the performance. Through a period of researches, Radebaugh [11] proposed that the increasing frequency can reduce the volume of PTCs, and a significant increase in the performance of the MPTC would be realized by taking some measures. Based on this theoretic studying, a MPTC operating at 120 Hz and 3.5 MPa was developed by NIST [12]. The regenerator was 9.02 mm in diameter and 30 mm in length filled with 635 mesh SSS, and the pulse tube was 4.46 mm in diameter and 30 mm in length. However, the operating frequency was far from the resonance frequency of compressor (60 Hz) which meant the efficiency of compressor was quite low. And a no-load temperature of 49.9 K and cooling power of 3.35 W at 80 K were achieved with the ultimate input electric power. The cooldown time from 285 K to 80 K was 5.5 min. Subsequently, in order to achieve a high efficiency and miniaturize the compressor, the linear compressor K527 was used [13]. However, it couldn't reach to the designed pressure ratio and the cooling power was just 0.53 W at 120 K. Rechler Cryogenic Laboratory emphasized that the impedance and capacitance of inertance tube was sufficient to phase shift and the function of reservoir wasn't obvious as the frequency increased, and a MPTC without reservoir was reported [14,15]. A PEEK pulse tube with low thermal conductivity was used to decrease the axial heat conduction losses instead of the stainless steel pulse tube. However, this configuration and novel material had been abandoned with the following pulse tube refrigerator's designing by the authors. A 100 Hz PTC supplied 1.45 W cooling power at 80 K with an input electric power of 49.1 W was reported by NGAS [16,17], and the weight of cooler was 857 g. This cooler's performance was tested with a range of frequencies up to 144 Hz. The experimental results showed that the efficiency of compressor gradually decreases with the increasing frequency, however, the cold head maintains its performance from 100 Hz up to 124 Hz. This indicated that the impedance between the compressor and cold head had not exactly matched yet with higher frequency. A 328 g coaxial microcryocooler was reported by Lockheed Martin and could support 0.5 W at 125 K [18]. By changing cooper to aluminum as the material of warm flange, the weight of cold head assembly is only 65 g. The CAS reported a coaxial MPTC based on an in-line prototype and the cooler

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could lift 2.1 W cooling power at 80 K with 80 W input electric power [19].

Based on the application that a type of spacing optical detector assembled by multiple optimal modules, and each module is equipped with a Dewar assembly which requires MPTC, a 1.22 kg MPTC working at 80 K and operating frequency of 120 Hz has been fabricated and tested. The main coaxial-type MPTC's geometry are optimized by utilizing numerical analysis. Besides, a newly developed regenerator matrix material of 604 mesh SSS is manufactured and tested in our laboratory, and the simulation results have been validated with the experimental results. The MPTC's performance is presented at the end of paper.

2. Theoretical design of the MPTC

As the power density is proportional to the frequency, higher frequencies can pack same power in a smaller volume. However, singly increasing frequency drives larger losses in the regenerator. Reducing the losses of the regenerator, as the core component of the cryocooler, is the key to the high efficiency MPTC. The conduction losses, the pressure drop losses, and the heat transfer losses are the three major losses of regenerator. Minimizing the average magnitude of mass flow through the regenerator is a way to decrease the losses due to the fact that pressure losses and heat transfer losses are proportional to the magnitude of mass flow. Therefore, the mass flow should be in phase with pressure in the middle of the regenerator. With the increasing frequency, the phase angle should be guaranteed as constant [11], i.e.,

$$\frac{fA(c_p,P_r,\varphi,T_h,T_c,k_{eff},\alpha,R,\theta_c)}{P_0(P_1/P_0)^2(Q_{reg}/Q_r)(Q_{cond}/Q_r)(\Delta P_1/P_1)} = constant \qquad (1)$$

where f is the working frequency, P_0 is the charging pressure, (Q_{reg}/Q_r) is the ratio of the regenerator heat transfer loss to the gross cooling power, (Q_{cond}/Q_r) is the ratio of the conduction losses to the gross cooling power, $(\Delta P_1/P_1)$ is the ratio of amplitude of pressure losses to the amplitude of dynamic pressure, and $A(c_p,P_r,\varphi,T_h,T_c,k_{eff},\alpha,R,\theta_c)$ is a function of φ (the porosity), c_p (specific heat at constant pressure), α (the function of Reynolds number and geometry, the value is 0.05 for screens), P_r (the Prandlt number), T_h (the hot end temperature), T_c (the cold end temperature), k_{eff} (the effective thermal conductivity of matrix, the value equals to the thermal conductivity of matrix times the conductivity degradation factor of 0.13 for SSS), R (gas constant per unit mass), θ_c (the phase between the mass flow and pressure at the cold end).

In Eq. (1), the last three parts in the denominator represent three major losses of regenerator. Increasing P_0 is the first step to maintain the ratio and compensate the partial losses with the increasing frequency. Meanwhile, the other operating and geometrical parameters should be analyzed and designed to achieve a high efficiency of MPTC.

The basic parameters of the regenerator and the inertance tube are performed by REGEN 3.3 and DeltaEC, which are used as the initial values of the optimization model. In the optimization process, an optimization model, which is based on a simplified 1-D theoretical model of geometrical dimensions of MPTC for the entire cold head assembly, was built and designed to approach the best COP with an operating frequency of 120 Hz, charging pressure of 3.8 MPa, cooling power of 1 W at 80 K with 300 K reject temperature. The calculated COP is the ratio of cooling power to input PV power.

2.1. Geometrical optimization of regenerator

The geometrical optimization of regenerator is determined by its length, outer diameter and inner diameter. In coaxial configuration, the inner diameter can be simply represented as the outer diameter of pulse tube. In this part, the coaxial-type regenerator diameter is replaced by the equivalent diameter of in-line. The SSS with a mesh number of 635 is used as the regenerator matrix according to the previous reports when the operating frequency is above 100 Hz [20].

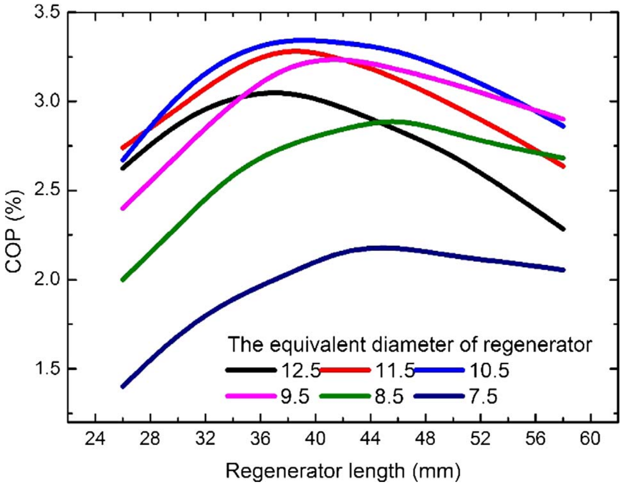

Fig. 1. Simulation on COP versus regenerator length with various equivalent diameters.

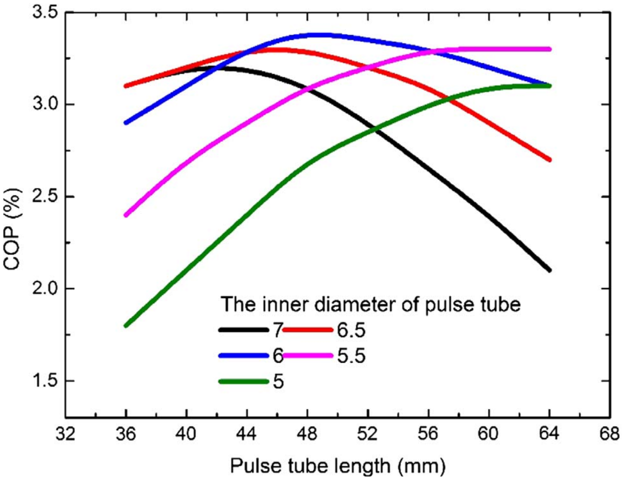

Fig. 2. Simulation on COP versus pulse tube length with various inner diameter.

Several different equivalent diameters and lengths of the regenerator are studied and analyzed in Fig. 1, where the designed equivalent diameter is set as 7.5 mm, 8.5 mm, 9.5 mm, 10.5 mm, 11.5 mm and 12.5 mm, respectively, and the length varies from 26 mm to 58 mm. It's obvious that the regenerator length and cross section area will significantly affect the COP. When the designed cross section area and length are too small, the heat transfer of the regenerator displays an insufficient process. Whereas the overwhelming size of cross section area and length of regenerator would lead to large temperature oscillation in radial direction and increase pressure drop, respectively.

The result also shows an up-to-down COP trend of each designed equivalent diameter with increasing regenerator lengths. The maximum COP at approximate 3.4% is approached by 10.5 mm equivalent diameter and 38 mm length.

2.2. Optimization of pulse tube

Fig. 2 shows the simulation on COP versus pulse tube length from 36 mm to 64 mm with various inner diameters. In these cases, the inner diameter of pulse tube should be dozens of the thermal penetration depth of working gas to guarantee the insulation of heat transfer during compression and expansion processes. The results show the 6 mm inner diameter of pulse tube maintains a high COP with length increases and the best COP occurs at 48 mm. Meanwhile, the outer diameter of