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Influence of regenerator void volume on performance of a precooled 4 K Stirling type pulse tube cryocooler

Zhuopei Li [a,*], Yanlong Jiang [a], Zhihua Gan [b], Limin Qiu [b], Jie Chen [c]

[a] Man-Machine Environment Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China
[c] Nanjing Cooltech Cryogenic Technology Company Ltd, Nanjing 211113, China

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ABSTRACT

Stirling type pulse tube cryocoolers (SPTC), typically operating at 30–60 Hz, have the advantage of compact structure, light weight, and long life compared with Gifford–McMahon type (1–2 Hz) PTC (GMPTC). The behavior of flow and heat transfer in the regenerator of a 4 K SPTC deviates from that at warmer temperatures and low frequencies. In this paper the behavior of 4 K regenerator at high frequencies is investigated based on a single-stage 4 K SPTC precooled by a two-stage GMPTC. The 4 K SPTC and the GMPTC is thermally coupled with two thermal bridges. The 4 K SPTC uses a 10 K cold inertance tube as phase shifter to improve phase relationship between mass flow and pressure. The regenerator void volume is an important factor that significantly influences the heat transfer between regenerator matrix and working fluid helium, pressure drop along the regenerator, and phase shift between mass flow and pressure. In this paper, influence of regenerator void volume on the performance of the 4 K SPTC with different operating parameters including operating frequencies and average pressure is studied theoretically and experimentally. The first and second precooling powers provided by the GMPTC are obtained which are important parameters to evaluate the efficiency of the whole 4 K system with precooling. The results of the regenerator void volume are given and discussed in normalized form for general use.

1. Introduction

Recent developments on mechanical cryocoolers are focusing on low temperature range especially around 4–6 K with a refrigeration power of about 10–500 mW. These cryocoolers support the use of low-noise mid-long wave infrared sensors in future space science explorations or provide precooling for advanced detectors such as microcalorimeters and thermal radiometers operating at milli-Kelvin temperatures [1]. Stirling type Pulse tube cryocoolers (SPTC) are a type of regenerative cryocoolers driven by long-life linear compressors with no moving parts at the cold end. Compared with a GMPTC which operates at about 1–2 Hz [2–4], a SPTC operating at typically 30–60 Hz have a much compact structure and light weight, making it appealing for space and military applications [5–10].

At present the efficiency of 4 K SPTC is still rather low (about 0.5–1% Carnot efficiency) [11–16]. The losses in the regenerator for a 4 K SPTC, given by the time-averaged enthalpy flux, increase rapidly due to the low heat capacity of regenerator materials near 4 K and the real gas properties of helium at this low temperatures [17]. In addition, high operating frequencies yield smaller thermal penetration depth of helium which makes the heat transfer worse [18]. As a result, a SPTC usually employs a multi-stage (three-stage or four-stage) structure to precool the final stage to reach 4 K [11–13,16]. The design of a multi-stage regenerator is very complicated due to a large number of operating and structure parameters for each stage of the regenerator. There exists complex interference between different stages of regenerators. Thus we use a single-stage regenerator of a 4 K SPTC precooled by a two-stage GMPTC which allows independent analysis and optimization of the critical Stirling type cold stage [19]. The SPTC and the GMPTC are thermally coupled by two thermal bridges. Thermal resistance of the two thermal bridges was calibrated according to the temperature differences between the ends of the thermal bridges with different heating power applied to them. The first and second precooling powers can be determined by the measured temperature differences between the ends of the thermal bridges which are important parameters to evaluate efficiency of the whole system. Previously we verified the possibility of reaching 4 K temperature region at high frequency (about 30 Hz) with helium-4 as the working fluid [20] and the effect of using a multi-layer regenerator

* Corresponding author.
E-mail address: peggy_goodluck@nuaa.edu.cn (Z. Li).

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matrix near 4 K [21]. In this paper influence of regenerator void volume on the performance of the 4 K SPTC is investigated theoretically and experimentally. The regenerator void volume is an important parameter that influences the heat transfer effectiveness of the regenerator, the pressure drop in the regenerator, and the phase shift between mass flow and pressure which further influences the magnitude of mass flow. The results of the regenerator void volume are given and discussed in normalized form for general use.

2. Calculated performance with different regenerator void volumes

2.1. Regenerator details

The schematic of the 4 K SPTC with precooling is shown in Fig. 1. The regenerator is divided into three parts (I, II and III) according to the temperature region. The first and second precooling temperature is 60 K and 10 K, respectively. This has been verified previously to give optimum efficiency for the system [22]. Q_{pc1} and Q_{pc2} is the first and second precooling power provided by the GMPTC to reach 4 K temperature region. W_h is the input power of the linear compressor driving the SPTC and Q_{net} is the cooling capacity of the SPTC at 4 K. The behavior of Regenerator III working between 4 K and 10 K is critical for the efficiency of the system because regenerator losses increase rapidly at low temperatures due to the real gas effects of helium and the low heat capacity of regenerator materials near 4 K. In the calculation the void volume of Regenerator III (4–10 K) is varied while the void volume of Regenerator I and II are kept constant. Regenerator void volume is varied by changing the length with the same cross-section area at the optimized value. Effect of the gas cross-section area of the regenerator is studied by optimizing the ratio of A_g/m_c, where A_g is the gas cross-section area of the regenerator and m_c is the mass flow at the cold end at 4 K. The ratio of A_g/m_c is a function of the velocity of the working fluid and is optimized at different regenerator lengths. In order to achieve a relatively larger cooling capacity, we choose 0.3 cm^2 s/g as the value of A_g/m_c to make sure the SPTC reaches 4 K. The mass flow rate at the cold end of the regenerator is determined by the desired cooling capacity of the SPTC. In this paper, the value of mc is 1.5 g/s and then Ag is derived as 0.45 cm^2. The regenerator void volume is expressed in normalized form V_{rg}/V_e, the ratio of regenerator void volume to expansion space swept volume (the peak value of the expansion volume) for general use [23]. Calculation is carried out based on a regenerator model known as REGEN 3.3 [24]. Ve has a calculated value of 0.1049 cm^3 in this paper according to the results of REGEN3.3. Table 1 lists the main parameters used in the calculation.

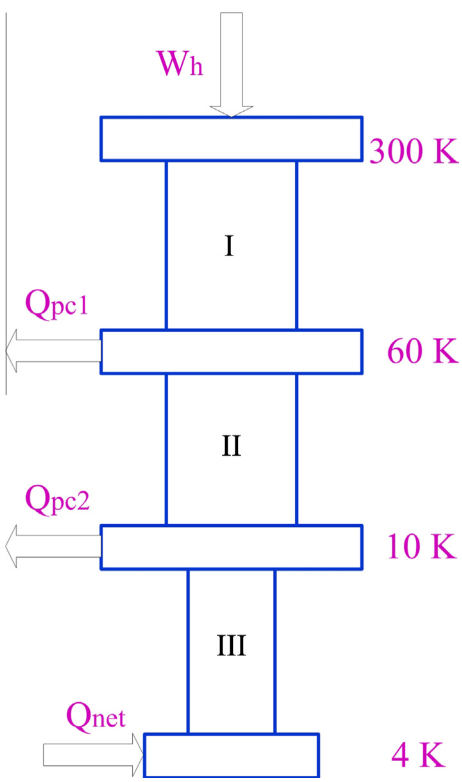

Fig. 1. Schematic of a regenerator with precooling (Q_{pc1}: first precooling power, Q_{pc2}: second precooling power, W_h: input power of a linear compressor driving the SPTC, Q_{net}: cooling capacity of SPTC).

2.2. Calculated performance of the 4 K SPTC

Fig. 2 shows the Coefficient of Performance and cooling capacity of the 4 K SPTC as a function of the ratio of regenerator void volume to expansion space swept volume (V_{rg}/V_e). The temperatures at the ends of the regenerator were 4 K and 10 K. The regenerator was filled with $HoCu_2$ spheres with a porosity of 38%. The operating frequency is 30 Hz. Pr is the pressure ratio at the cold end of the regenerator which is fixed as 1.2. The results show that the optimum ratio of V_{rg}/V_e lies in the range between 14 and 16. The cooling capacity increases with the regenerator void volume until the regenerator void volume ratio approaches to the value of about 16.

The two-stage GMPTC plays the role of a two-stage SPTC when a 4 K three-stage SPTC is designed. In order to reach 4 K low temperature, regenerator losses at warmer temperature regions have to be intercepted by the first and second cold end of the precoolers which is referred to as the first (enthalpy difference between Regenerator I and II) and second precooling powers (enthalpy difference between Regenerator II and III) in this paper. These are important parameters to evaluate the efficiency of the whole system.

Table 1
Main parameters used in the calculation for the 4 K regenerator.

Operating parameters	Frequency (Hz) 30		Average pressure (MPa) 1.0		Pressure ratio at the cold end (P_{max}/P_{min}) 1.2	
Regenerator	Tc (K)	Th (K)	D (mm)	L (mm)	Regenerator matrix	Porosity
I	T1	300	15.4	30	#400 Stainless steel screen	0.686
II	10	T1	15.4	30	#400 Stainless steel screen +Lead spheres	0.686 0.38
III	4	10	12.4	20–50	$HoCu_2$(Ø100 μm)	0.38
Pulse tube	4	10	4.8	30		
Inertance tube	–	10	1	360	Reservoir	250 cm^3