Cryogenics 92 (2018) 36–40

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Research paper

Theoretical and experimental study of a gas-coupled two-stage pulse tube cooler with stepped warm displacer as the phase shifter

Xiaomin Pang[a,b], Xiaotao Wang[a,*], Wei Dai[a,b,*], Haibing Li[c], Yinong Wu[d], Ercang Luo[a,b]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Lihan Cryogenics Co., Ltd, Shenzhen 518055, China
[d] Shanghai Institute of Technical Physics of Chinese Academy of Sciences, Shanghai 200083, China

ARTICLE INFO

Keywords:
Co-axial configuration
Stepped warm displacer
Pulse tube cooler
Double inlet

ABSTRACT

A compact and high efficiency cooler working at liquid hydrogen temperature has many important applications such as cooling superconductors and mid-infrared sensors. This paper presents a two-stage gas-coupled pulse tube cooler system with a completely co-axial configuration. A stepped warm displacer, working as the phase shifter for both stages, has been studied theoretically and experimentally in this paper. Comparisons with the traditional phase shifter (double inlet) are also made. Compared with the double inlet type, the stepped warm displacer has the advantages of recovering the expansion work from the pulse tube hot end (especially from the first stage) and easily realizing an appropriate phase relationship between the pressure wave and volume flow rate at the pulse tube hot end. Experiments are then carried out to investigate the performance. The pressure ratio at the compression space is maintained at 1.37, for the double inlet type, the system obtains 1.1 W cooling power at 20 K with 390 W acoustic power input and the relative Carnot efficiency is only 3.85%; while for the stepped warm displacer type, the system obtains 1.06 W cooling power at 20 K with only 224 W acoustic power input and the relative Carnot efficiency can reach 6.5%.

1. Introduction

Small scale coolers are widely used in applications such as cooling infrared sensors and superconducting devices, etc. Among them, Stirling coolers have the advantage of high efficiency. However, the displacer working in low temperature region poses itself as a technical challenge in terms of reliability and lifetime span. For this reason, pulse tube coolers which eliminate the cryogenic displacer, have been the focus of cryocooler research for the past 20 years [1]. The efficiency of the pulse tube cooler is closely related to the phase shifter. Since the pulse tube cooler was developed, there have been many phase shifters, such as orifice type, inertance tube type and double inlet type [2–4]. For these phase shifters, the expansion work at the hot end of the pulse tube is simply dissipated, which lowers the cooler theoretical efficiency as compared with a Stirling cooler. Meanwhile, the phase-shifting capability is limited especially for systems operating at low temperature and with small-scale cooling power.

Using warm piston as the phase shifter could be traced back to 1990s [5]. Zhu et al. further proposed a warm gas-driven displacer with a displacer rod in 2010 [6] and presented various theoretical analyses. Compared with the traditional phase shifter, it can recover the expansion work and thus the theoretical efficiency is equal to the Carnot efficiency. Later Yazhi Shi [7] carried out the experiments to verify the concept. A no-load temperature of 38.9 K and 10.14 W @ 77 K of cooling power was obtained. Xiaotao Wang et al. developed a high efficiency hybrid Stirling pulse tube cooler in 2015, which used a rod-less ambient displacer as the phase shifter [8]. The relative Carnot efficiency in the experiments reached 24.2% with a cooling power of 26.4 W @ 80 K, which was higher than that of an ordinary pulse tube cooler.

Many efforts had been made to improve the cooling performance of two stage pulse tube coolers working in liquid hydrogen or lower temperature. In [9,10], Zhu et al. introduced stepped displacer concepts for thermal-coupled and gas-coupled two stage pulse tube coolers. Some numerical simulations had been conducted but with no experimental results. In 2016, Air Liquid developed a two stage thermal-coupled pulse tube cooler for space missions [11]. In order to improve cooling efficiency, linear motor was used as the active phase shifter in the second stage. With 300 W electric power input, a no-load temperature of 9.2 K was obtained with 0.8 W cooling power at 20 K. However, the two stages used separate phase shifters, which complicated the system. The expansion work at the hot end of the first stage

* Corresponding authors at: Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of Chinese Academy of Sciences, Beijing 100190, China (W. Dai).
E-mail addresses: xtwang@mail.ipc.ac.cn (X. Wang), cryodw@mail.ipc.ac.cn (W. Dai).

https://doi.org/10.1016/j.cryogenics.2018.03.008
Received 11 September 2017; Received in revised form 20 March 2018; Accepted 20 March 2018
Available online 21 March 2018
0011-2275/

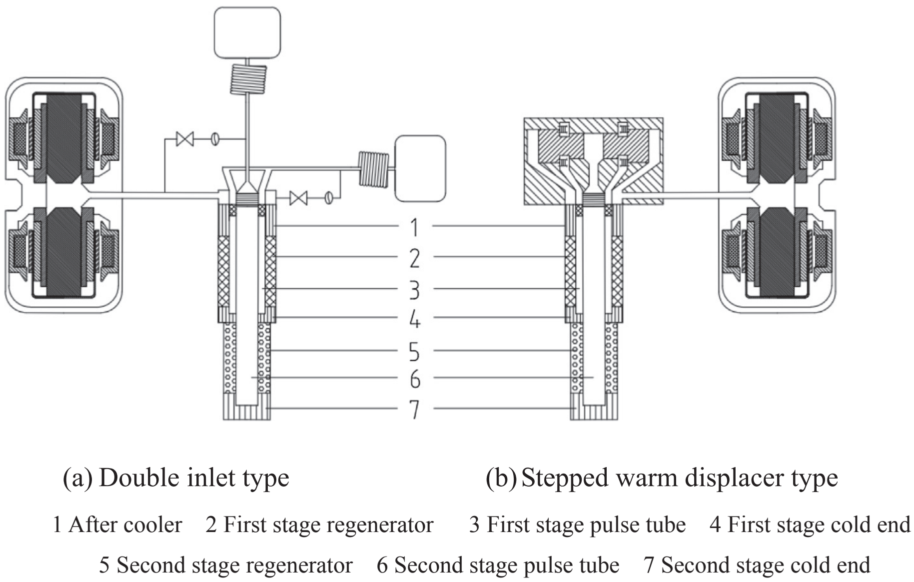

Fig. 1. Schematic of the system. (a) Double inlet type. (b) Stepped warm displacer type. 1. After cooler. 2. First stage regenerator. 3. First stage pulse tube. 4. First stage cold end. 5. Second stage regenerator. 6. Second stage pulse tube. 7. Second stage cold end.

was dissipated, which limited the efficiency. In 2017, a Stirling/pulse tube hybrid two stage cooler was developed by Raytheon [12,13]. The first stage was a Stirling cooler and the second stage was a pulse tube cooler. 0.18 W cooling power at 10 K was obtained with 434 W electric power input.

For further improvement and more compactness on two stage pulse tube cooler working in liquid hydrogen temperature, a two stage completely co-axial pulse tube cooler with stepped warm displacer as the phase shifter is introduced in this paper. In the following, the system configuration with two types of the phase shifters (double inlet and stepped warm displacer) is firstly introduced. Next, numerical comparisons are made between the two type phase shifters. Then, the experimental setup, results and discussions are presented. Finally, some conclusions are drawn.

2. System design

2.1. System configuration

Fig. 1(a) and (b) shows the schematic of configurations of the pulse tube coolers with double inlet and stepped warm displacer as the phase shifter, respectively. The system is a two-stage gas-coupled pulse tube cooler with a completely co-axial configuration. Annular shaped pulse tube is used in the first stage. Compared with the in-line type and U type, this configuration is more compact. The performance of the annular pulse tube has been studied in [14].

The double inlet configuration is well known and a zoomed-in detail of the stepped warm displacer is shown in Fig. 2. A dual-opposed stepped warm displacer configuration is adopted. For each warm displacer, there are a compression space, two expansion spaces, one stepped piston and supporting flexure bearings. The first stage expansion space is connected to the hot end of the first stage pulse tube, the second stage expansion space is connected to the hot end of the second stage pulse tube, and the compression space is connected to the after cooler. The expansion work from the pulse tubes enter the expansion spaces, then transfer energy to the compression space through the piston movement which is then combined with the input power from the compressor to drive the cooler.

2.2. Design of the stepped warm displacer

For a high efficiency pulse tube cooler, a more specific requirement is that the pressure wave and mass flow are in phase somewhere in the middle of the regenerator to minimize the regenerator loss. For this reason, the pressure wave is required to lead the mass flow by a certain degree at the hot end of the pulse tube (typically 60–80° for a cooler working at liquid hydrogen temperature). To realize this phase relationship, an efficient phase shifter is needed.

In case of an inertance tube, the phase-shifting capability is limited especially for coolers working at low temperature with a small-scale cooling power. The double inlet is typically added to improve the phase shifting ability. Because the phase shift through the double inlet depends on the pressure drop across the regenerator and the valve resistance, its phase adjusting capability is somewhat limited. In contrast, the stepped warm displacer can offer a more flexible adjusting mechanism according to the corresponding dynamics equation:

$$\hat{P}_1(A_1-A_2)+\hat{P}_2A_2-\hat{P}_fA_1=(k+i\omega R_m-\omega^2\mathrm{m})\hat{x} \quad (1)$$

where $\hat{P}_f$, $\hat{P}_1$, $\hat{P}_2$ are the dynamic pressures at the compression space, first and second stage expansion space, respectively. A_1 and A_2 are the cross-sectional areas (the corresponding diameters D_1 and D_2, as shown in Fig. 2) of the stepped pistons, m is the displacer moving mass, ω is the angular frequency, k is the spring stiffness, R_m is the mechanical damper, $\hat{x}$ is the displacement of the displacer. Apparently, through changing spring stiffness, moving mass and the stepped piston areas, impedance at the hot ends of the first and second stage pulse tube can be easily tuned.

The main parameters of the pulse tube cooler are listed in Table 1, considering the limitations of the actual system structure, the expansion spaces volume of the first and second stages are set as 12 cm^3 and 1 cm^3, respectively.

Simulations are performed using Sage software [15], which is developed by Gedeon Associates. In the simulations, helium is selected as the working gas, and the ambient heat exchanger is fixed at 300 K. The mean pressure is kept 3.0 MPa, and the frequency is 30 Hz, and the pressure ratio at the compression space is set at 1.37. Targeting at optimum efficiencies at 20 K, spring stiffness and moving mass are selected to be 20 kN/m and 30 g, respectively. Meanwhile, the diameters of the stepped piston are 28 mm (D_1 shown in Fig. 2) and 12 mm (D_2