Cryogenics 68 (2015) 1–18

Contents lists available at ScienceDirect

Cryogenics

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

Review

Development of high performance moving-coil linear compressors for space Stirling-type pulse tube cryocoolers

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 18 January 2015
Accepted 28 January 2015
Available online 7 February 2015

Keywords:
Moving-coil
Linear compressor
Pulse tube cryocooler
Space application

ABSTRACT

This paper presents a review of the recent development of moving-coil linear compressors for space Stirling-type pulse tube cryocoolers in National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences. The design, manufacture and assembly methods are described with special emphases laid on linear motor, clearance seal, flexure springs, dual-opposed configuration and flexible design. Several key components are focused on and studied in a detailed way in terms of material selection, geometry design, configuration optimization, manufacture approaches and optimal assembly to achieve high efficiency, easy producibility, high reliability and long life. Experiences from the forerunners and the state-of-the-art approaches are reviewed and used for useful references, while our own successful experiences are emphasized and discussed in more detail together with some lessons learned. A series of compressors for space applications have been worked out with high confidence of reliability and long life expectation, which achieve input capacities of 0–500 W with motor efficiencies of 74.2–83.6%. Single-stage pulse tube cryocoolers driven by these compressors have already covered the temperature range of 25–200 K with cooling capacities varying from milliwatt levels to over 30 W. The commonly-used compressor types and purposes, performance characteristics and their applications in typical space cryocooler projects are also presented.

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http://dx.doi.org/10.1016/j.cryogenics.2015.01.009
0011-2275/

1. Introduction

1.1. Pulse tube cryocooler, a new-generation space regenerative cryocooler

The infrared detectors play an important role in the civilian space, Earth science and the military defense fields [1–4]. The cryogenic temperatures, normally lower than 120 K, are critical to allow most infrared detectors to operate with low background noise and high sensitivity [4]. Therefore, the worldwide space industry has been actively seeking means for multiyear cryogenic cooling in space to enable long-life infrared sensors since the 1950s [4,5]. In the process, two types of regenerative cryocoolers, the Stirling cryocooler and the pulse tube cryocooler (PTC) have been studied in great depth in the past three decades and had a wide range of important practical applications to date [4–22]. Especially, the PTC, which eliminates any moving mechanical component at the cold end, has further achieved two evident advantages over the Stirling cryocooler: first, any wear-out at the cold end is eliminated, and second, at the cold end both vibration input and electromagnetic interference (EMI) levels are significantly reduced [23–27]. As a result, the PTC has been endowed with several remarkable merits such as low noise, high reliability and long life, which have a strong appeal to the space-borne cryogenic infrared detectors. After a 50-year development since the original invention and several generations' great efforts, the PTC has already evolved from a laboratory curiosity into an enabling cryogenic technology which is efficient and reliable enough to be used on a wide variety of space missions. The past thirty years have witnessed a worldwide quest for space-qualified PTCs, and a series of successful applications since the first launch in the late 1990s have provided abundant convincing evidences of the PTC as a new-generation enabling space regenerative cryocooler [4–8,14,20].

1.2. Three types of PTCs classified according to drivers

After 50 years of progress, the present PTC has become quite different from the original invention [23]. Currently, a typical single-stage PTC usually includes a driver, a regenerator, a pulse tube, a phase-shifter (it is normally an inertance tube for space applications), a gas reservoir and several heat exchangers (HXs) at both cold and warm ends of regenerator and pulse tube [14]. Some basic information about the PTC theory can be found in several Refs. [23,25,28–32].

The driver is used to produce the oscillating pressure wave and serves as the origin of the energy in the PTC system. According to the driver used, the PTC can be generally classified into three types, as shown in Fig. 1. The first one is the Stirling-type PTC (SPTC), which is so called because it uses the similar linear compressor originally designed for the Stirling cryocooler. Correspondingly, the second one is named as the GM-type PTC because it is driven by the similar GM-type compressor to that of the GM cryocooler. The GM-type PTC is considerably cumbersome and also has a low thermodynamic efficiency due to the used rotary valves, and thus the possibility of its use in space is completely ruled out. There is also another type of PTC used not as widely as the former two ones, which is driven by the thermo-acoustic engine whose structure is generally large and loose, and furthermore, its efficiency is relatively low below 80 K. Therefore, the space application of the thermo-acoustic type PTC was seldom attempted. Of the three types of PTCs, the SPTC is the only candidate suitable for use in space to date.

1.3. Oxford-type moving-coil dual-opposed linear compressor

1.3.1. Main considerations on developing linear compressor

The special space environment emphasizes high reliability and long operation life featuring no maintenance possible, which is a huge challenge for the conventional reciprocating compressors based on the traditional bearings and seals. The dynamic seal between piston and cylinder was always one of the most vulnerable parts leading to potential wear and contamination. Lubricants often introduce severe contamination into the system or even cause blockage at cold end, while the conventional dry-bearings nearly without exception result in wear [33,34]. The primary intention of developing the linear compressor is to extend the operation lifetime by eliminating the radial force exerted on the piston, which inevitably exists in the traditional rotary compressors and provides the useless work and thus is one of the main sources of wear. Theoretically, a properly-designed linear compressor can completely eliminate the radial forces, since the force created in the wires is perpendicular to both the magnetic field and the direction of the current in the wire, and thus the motor exerts an absolutely linear force in the axial direction on the piston [33,34].

However, it is still a serious challenge to reduce the theory into practice. Many approaches have been attempted in order to ensure the stringent linear motion and contact-free between piston and