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Design of a two-stage high-capacity Stirling cryocooler operating below 30K

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Abstract

The high capacity cryocooler working below 30 K can find many applications such as superconducting motors, superconducting cables and cryopump. Compared to the GM cryocooler, the Stirling cryocooler can achieve higher efficiency and more compact structure. Because of these obvious advantages, we have designed a two stage free piston Stirling cryocooler system , which is driven by a moving magnet linear compressor with an operating frequency of 40 Hz and a maximum 5 kW input electric power. The first stage of the cryocooler is designed to operate in the liquid nitrogen temperature and output a cooling power of 100 W. And the second stage is expected to simultaneously provide a cooling power of 50 W below the temperature of 30 K. In order to achieve the best system efficiency, a numerical model based on the thermoacoustic model was developed to optimize the system operating and structure parameters.

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Keywords: Stirling Cryocooler, Free piston, Two stage, High Capacity, 30K

1. Introduction

The high capacity cryocooler working below 30 K can find many applications such as superconducting motors, superconducting cables and cryopump. For the application of superconducting magnets, the superconducting

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materials working below the temperature of 30 K is relatively mature and have better mechanical properties to be assembled to a magnet. Generally tens of Watt cooling power need to be provided to magnets. The GM cryocoolers or the GM type pulse tube coolers are the main technologies for this temperature region and capacity. Compared to the GM cryocooler, the Stirling cryocoolers can achieve higher efficiency and more compact structure.

In 1960s, G. Prast in Philips Company reported their conventional two-stage Stirling cryocooler, which attained a low temperature of 12 K and a refrigeration of 100 W with an efficiency of 17 % of Carnot efficiency [1]. Though this system acquire very high efficiency but the crank rod bring some vibration. The two stage high capacity Stirling-type pulse tube cooler has be developed in recent years. In 2010, M. Dietrich and G. Thummes introduce their two-stage high frequency pulse tube cooler, which achieved a no-load temperature of 13.7 K and a cooling power of 12.9 W at 25 K. The corresponding efficiency at 25 K is 5.6% relative to Carnot [2]. Compared to pulse tube cooler, the two stage Stirling cryocooler driven by linear compressor can acquire a higher efficiency and is independent of orientation, which may be a problem for high capacity pulse tube cooler. But here are only some reports in the relative smaller capacity, which supply 1-2 W cooling power around the temperature of 30 K [3,4].

This article introduces the development of a two stage high capacity free piston Stirling cryocooler system, which is driven by a moving magnet linear compressor with an operating frequency of 40 Hz and a maximum 5 kW input electric power. The design goals and numerical model are present in the following section. The 3rd section introduces system geometrical configuration and the characteristics of main components in the system are analyzed. The 4th section show the main simulation results and operating characteristics are discussed. At last, the conclusions are given.

2. The Design Goals and Numeric Model

In the practical applications, a radiation shied need to be mounted between the components working below 30 K and room temperature other components to decrease the radiation. And the liquid nitrogen usually is chosen as the heat transferring fluid. So the high capacity cooling power need be supplied both at the temperature region of 30 K and the liquid nitrogen temperature. After some simple estimation, the design goals are set as output a cooling power of 100 W at 77 K and simultaneously providing a cooling power of 50 W at the temperature of 30 K.

The numeric model based on the thermoacoustic theory is used to optimize the operating and structure parameters [5], which is a powerful tool for regenerative coolers and has been proven to be validated through a lot of designs of pulse tube cooler and free piston Stirling engines in our laboratory [6]. The details of model calculation method can be found in Ref. [7]. Meanwhile, the software SAGE is used for comparison.

For the stirling cryocooler drived by linear compressor, the operating frequency usually lotates between 30-60Hz. The increase of frequecny can effectively bring a more compact and small system volume. But the lower frequency can reduce the heat exchanging loss in the regenerator, which is very importmant for low temperature operation. Considering these factors, the frequency of 40 Hz is chosed to get a efficient and compact system.

3. Geometrical Configuration and Main Components

For reaching very low temperature , there must be more than two expansion spaces. At the cold side of the first regenerator, the motion of displacer in the first expansion space will bring some cooling power for precooling the second regenerator. This configuration is also be able to provide some cooling power into the external environment at relative higher temperature region.

The schematic drawing is shown in the Fig.1. As shown in figure, this two-stage cryocooler system is composed of a linear moving magnet compressor, two regenerators, a two-stage displacer and three heat exchangers. The engineering model is shown in Fig.2.

Both of the regenerators choose steel screen as the regenerator materials.The diameter and length are selected according to the numeric calculation results.

The three heat exchangers are manufactured by EDM technology and made of cooper. The ambient heat exchanger is designed to be cooled by external chilling water.

One of the important components in the Stirling cryocooler is the displacer, which is used to provide suitable acoustic field in the regenerator for improving the cooling efficiency. The first stage of displacer have bigger