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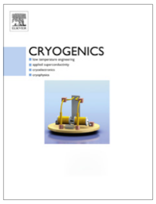

Research paper

Study on a high capacity two-stage free piston Stirling cryocooler working around 30 K

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ABSTRACT

This paper presents a two-stage high-capacity free-piston Stirling cryocooler driven by a linear compressor to meet the requirement of the high temperature superconductor (HTS) motor applications. The cryocooler system comprises a single piston linear compressor, a two-stage free piston Stirling cryocooler and a passive oscillator. A single stepped displacer configuration was adopted. A numerical model based on the thermoacoustic theory was used to optimize the system operating and structure parameters. Distributions of pressure wave, phase differences between the pressure wave and the volume flow rate and different energy flows are presented for a better understanding of the system. Some characterizing experimental results are presented. Thus far, the cryocooler has reached a lowest cold-head temperature of 27.6 K and achieved a cooling power of 78 W at 40 K with an input electric power of 3.2 kW, which indicates a relative Carnot efficiency of 14.8%. When the cold-head temperature increased to 77 K, the cooling power reached 284 W with a relative Carnot efficiency of 25.9%. The influences of different parameters such as mean pressure, input electric power and cold-head temperature are also investigated.

1. Introduction

For off-shore wind power utilization, power scale of the turbine generator has increased to about 10 MW. One of the concern is how to design the generator with the smallest possible weight to bring down the installation cost [1]. Meanwhile, the generator needs to be sufficiently reliable to ensure a long lifetime and least maintenance. Compared with conventional motors and generators, the application of superconducting technology in the motors and generators can provide higher torques in a much smaller size and weight, which also results in high efficiency because of a much smaller loss in the coils [1,2]. The development of high temperature superconductor (HTS) materials promotes the practical applications as compared with low temperature superconductors such as NbTi [3]. Meanwhile, HTS generator makes direct drive possible and avoids the failure of gearbox.

For HTS generators in the field, a compact, light-weight, high efficiency and high reliable cryocooler will be needed for the cooling of superconductor. Considering the current development state of 2nd generation HTS materials, a temperature around 30 K is required for use in strong magnetic field to bear sufficiently high current density [4]. For cooling a generator with an output of about 10 MW, tens of Watt of cooling power at 30 K must be provided generally.

At present, the GM cryocoolers are relatively mature to supply sufficient cooling capacity in this temperature region and are commercially available [5]. SHI developed a large cooling capacity single-stage GM cryocooler, labelled as RDK-500B for HTS applications in 2014. A typical cooling capacity is 46/52 W at 20 K or 85/96 W at 30 K with 6.9/7.9 kW input power at 50/60 Hz, which indicate an efficiency of about 9.5% of Carnot efficiency. The cooling capacity degradation caused by inclination is within 24%. However, the existence of oil lubricated compressor with oil filters and high and low pressure tanks in GM system makes the system bulky and regular maintenance is required. Taking the model RDK-500B for example, it has a total weight of 125 kg and needs maintenance around every 9,000000 h. In addition, the efficiency is reduced by the irreversible loss due to the rotary valve.

The kinematic Stirling cryocoolers driven through crank-shaft mechanism can generate a higher system efficiency than the GM cryocoolers. In 1960s, Prast of Philips Company reported a conventional two-stage Stirling cryocooler which attained a lowest temperature of 12 K and a cooling power of 100 W at 20 K with an efficiency of 17% of Carnot efficiency [6]. Although the efficiency is high, the intrinsic disadvantages are also apparent. Using

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oil-lubrication and dynamic seal leads to the requirement of a regular maintenance every 6000 operating hours.

In recent years, two-stage high capacity Stirling-type pulse tube cryocooler driven by linear compressor has been developed. Using oil-less linear compressor solves the problem of regular maintenance. In 2010, Dietrich and Thummes introduced their two-stage high-frequency pulse tube cryocooler, 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 [7]. As the performance needs to be much improved in the future, intrinsic lower efficiency due to no work recovery, compared with that of Stirling cryocoolers, affects the system efficiency mainly through the first stage performance which is normally above 40–50 K. Kim introduced an on-board pulse tube cryocooler with a cooling power of 5 W at 56 K to cool the 2G YBCO superconducting materials [8]. The cryocooler was physically and thermally in contact with the HTS rotor while being rotated together. But for large cooling power, the higher aspect ratio of the pulse tube diameter and length can easily cause natural convection loss inside hollow pulse tube, which is difficult to suppress. This somehow limits its use when users need a flexible or even rotating orientation.

The free piston Stirling cryocooler uses the displacer as the phase shifter and recovers expansion work at the cold end. Certain high-capacity single-stage Stirling cryocoolers have been researched in recent years. These cryocoolers can supply several hundred Watt cooling power at around 77 K, but lowest temperature does not reach below 40 K [9,10]. To reach lower temperatures, two stage configuration is necessary. However, current research mainly focuses on relatively smaller capacity with 1–2 W cooling power at approximately 30 K [11,12], which is mainly targeted at high end applications such as space applications.

In order to meet the requirement of the off-shore HTS generator applications, we initiated the study of a two-stage high-capacity free-piston Stirling cryocooler driven by a linear compressor. The uses of free piston Stirling cryocooler and linear compressor technology are expected to lead to a compact, high-capacity, high efficiency and highly reliable cryocooler operating at the 30 K temperature region, which could be installed inside the generator and rotate with the generator. Some numerical investigations have been reported in [13]. An experimental system has thus been set up and is reported here. In the following sections, the system configuration is firstly described. Secondly, some simulation results are discussed. Thirdly, main experimental results as well as the comparison with numerical results are given. Finally, some conclusions are drawn.

2. System configuration and description

As shown in Fig. 1, the system comprises a single piston linear compressor, a two-stage free piston Stirling cryocooler, and a passive oscillator. The Stirling cryocooler in turn includes compression space, ambient heat exchanger, first stage regenerator, first stage cold heat exchanger, first stage expansion space, second stage regenerator, second stage cold heat exchanger (also referred to as cold-head), second expansion space and the stepped displacer.

One of the most important components in the Stirling cryocooler is the displacer, which is used to recover the expansion work and provides a suitable acoustic field in the regenerator to improve the cooling efficiency. Here, the displacer is of a stepped configuration to serve for both stages, as shown in Fig. 1. Through carefully tuning the areas facing the two expansion spaces and compression space, both stages can work efficiently and both expansion works get fed back to the compression space. The displacer is supported through flexure bearings, with a configuration similar to that by Infinia [10]. This kind of configuration makes it easier to detach the cold head from the linear compressor for easy modifications. Inside the displacer, there are several stainless steel sheets welded to the inner wall to block the radiation coming from higher temperatures. Meanwhile, natural convection may partly be impeded, which, we later found, was not enough.

In low-capacity Stirling cryocoolers, the regenerator is usually located inside the displacer for compactness as well as for structure concerns. For the high-capacity system here, the regenerator is of annular design and is fixed. Stainless steel screens are filled in both the first and second regenerators. All the heat exchangers are slit type and thin slits are cut with electric discharge machining on copper blocks. The first cold heat exchanger is located between the first stage and secondary regenerator. The mass flow down through it is divided into two parts: one part enters the secondary regenerator and the other part enters the expansion space of the first stage.

A moving magnet linear compressor is used here. A single-piston configuration helps to realize a compact system with a minimum volume between the compressor and the cryocooler. Gas-bearing technology is applied for supporting the moving piston to ensure a small clearance between the piston and cylinder.

A major issue with the single piston configuration is that the inertial force of the heavy piston, plus the displacer, needs to be balanced. This is done through a passive oscillator, i.e. a heavy mass plus spring with resonance frequency being the same as the system operation frequency. The oscillator is installed concentrically at the bottom of the compressor housing.

3. Numeric simulation results and discussion

3.1. Thermoacoustic simulation model

To simulate the system performance, a quasi-one-dimensional numeric model based on the thermoacoustic theory is used to optimize the operating and structure parameters, which is a powerful tool for regenerative coolers and has been tested on numerous designs of pulse tube cryocoolers and free piston Stirling engines in our laboratory [14,15]. The details of the model can be found in Ref. [16]. Effects of natural convection inside the displacer is neglected in the model.

3.2. Simulation results and discussion

The design goal is to generate tens of Watts of cooling power at 30 K. A frequency of 40 Hz is chosen with a compromise between power density and efficiency. The mean pressure for the optimization is set at 3.0 MPa.

After optimization, the system main structure and operating parameters are obtained and summarized in Table 1. The displacer has a rod with a diameter of 30 mm and is supported by springs with a total stiffness coefficient of 116 kN/m. The natural resonance frequency of the displacer is 44 Hz, which is a litter higher than the system operating frequency of 40 Hz. The displacement amplitude limit of the displacer is about 4 mm.

The compressor parameters such as mass, piston diameter and spring coefficient, are chosen to match the cryocooler impedance at the given operating conditions, which is obtained through the thermoacoustic model. A swept volume of 240 cm^3 is needed to provide sufficient acoustic power to drive the cryocooler, which corresponds to a piston displacement amplitude of 12 mm with a cross-sectional area of 0.01 m^2.

The main simulation results are summarized in Table 2. The simulation results show that a cooling power of 65 W at 30 K can be obtained with an acoustic power (or called PV power) of 2.65 kW, which means a relative Carnot efficiency of 25.5%. The

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