Experimental test of 4 kW-class Stirling cryocooler for superconducting cable cooling system

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Abstract. This research paper focuses on the experimental test of a free-piston Stirling cryocooler driven by a double-acting linear compressor. The cold head of the Stirling cryocooler has been designed and adopted for circulating and sub-cooling liquid nitrogen for the superconducting application, i.e. superconducting cable. The whole system mainly consists of aforementioned Stirling cryocooler and a liquid nitrogen circulation facility including a heater. In this research paper, the experimental validation as a proof of concept has been carried out. During the experiments, temperatures, pressures and several dynamic variables has been acquired as the input conditions. The cooling capacity has been estimated by obtaining thermodynamic properties at the both entrances of the circulator. The relevant operational issues will also be discussed.

1. Introduction

As the high temperature superconductor (HTS) has been discovered, the first generation Bi$_2$Sr$_2$Ca$_n$$_n$1Cu$_{2+4x}$O$_{2n+4+x}$ (BSCCO) conductor and the second generation ReBa$_2$Cu$_3$O$_7$-d ((RE)BCO) conductor can readily replace low temperature superconductor (LTS) due to its high critical temperature. The wide operational temperature of HTS elements enable them to be facilitated for various superconducting devices cooled by various types of mechanical cryocoolers. At this point, the needs of mechanical cryocoolers operating on various temperature ranges are ever increasing as an enabling technology. Among them, high capacity cryocoolers involved for cooling superconducting power applications are getting more attractive [1-3]. In aspect of commercialization of the HTS power application, it creates significant burden that the commercialized cooling systems have to be highly reliable and thermally efficient.

In this research paper, we have developed a Stirling cryocooler system accompanied by dual-acting linear compressors. The system is originally subjected to cooling a superconducting cable so that the auxiliary facilities have been also designed and constructed. The developed Stirling cryocooler system is advantageous that there is no oil involved for lubricating the moving parts of the compressor and is inherently free from vibration. The implementation of a free-piston type expander also enables the system reduce friction losses. The electric to mechanical conversion efficiency of the developed linear compressors exceeded 70%. The system can exert exceedingly 4 kW cooling power at 77 K and it has been certified by a calorimetric method with a liquid nitrogen (LN$_2$) circulation system. The integrated system recorded 28.4% of Carnot efficiency. This research paper will describe (1) on the design and construction of the system and (b) on the relevant operational issues.
2. Experimental setup

The system has been designed for cooling a superconducting cable with up to 4 kW heat load. The system is mainly composed of two parts, i.e. the Stirling cryocoolers and the LN$_2$ circulation system. Fig. 1 shows the whole system and its schematic.

2.1. Cryocooler

Eight Stirling cryocooler units have been developed for sub-cooling LN$_2$ and each cryocooler is capable to exert cooling power up to approximately 500 W at the temperature of 77 K. All the units adopt a gamma-type configuration and are driven by their own independent double-acting linear

Figure 1. (a) Completed test facility for the superconducting cable cooling system with 4 kW Stirling cryocooler (vacuum jacket lid opened) and (b) its schematics

Figure 2. 3D rendering of the single unit Stirling cryocooler
compressors. Each compressor consists of two opposite pistons with the diameter and the allowable stroke of 100 mm and 15 mm, respectively. The allowable current (thrust coefficient) and the maximum input power have been designed to be 15.8 A_{rms} (85.5 N A^{-1}) and 12 kW at the frequency around 60 Hz. The displacer is restrained in transverse direction by a flexure and freely moves in axial direction by the pressure difference acting on its both ends, i.e. compression and expansion spaces. The displacer has the diameter and the allowable stroke of 83 mm and 12 mm, respectively. The heat is removed to atmosphere by means of the warm-end heat exchanger (WHX) placed at the compression space. The regenerator nests the displacer and it has 86 mm in inner diameter, 130 mm in outer diameter and 80 mm high. 30 μm-stainless steel random fiber sheets were juxtaposed in the regenerator canister. The cold-end heat exchanger (CHX) is located at the expansion space and it has a spirally wound heat exchanger that can accept the LN$_2$ flow traveled from the entire superconducting cable. Fig. 2 shows the single unit of the Stirling cryocooler.

2.2. LN$_2$ circulation system
In order to mitigate flow mal-distribution of LN$_2$ from the circulation system, eight cold-ends have been installed into two independent vacuum jackets. Two vacuum jackets and the LN$_2$ circulation system were connected with metallic bellows and they were evacuated below $10^{-4}$ mPa. At the inner space of the LN$_2$ bath, a heater unit was installed for heating up sub-cooled LN$_2$ used as a heat transfer medium between the Stirling cooler’s cold ends and the heat load. A cryogenic circulator (BNCP-30, Barber-Nichols) was placed at the bottom of the LN$_2$ bath and it stirs the heat transfer medium. A Coriolis mass flow meter (CMF050M, Micro Motion) monitors instantaneous mass flow rate of LN$_2$ supplied to the Stirling cold-ends.

![Figure 3](image)

**Figure 3.** (a) Temperature profiles the eight cold-ends and (b) the pipelines during the initial cool-down process and (c) the input power of the Stirling cryocooler
3. Experiments

3.1. Experimental procedures and initial operations
The experimental procedures are as follows; (i) Vacuuming the jackets below $10^{-4}$ mPa and pressurizing the compressors with helium of 2.5 MPa, (ii) At the beginning of the experiment, filling LN$_2$ into the internal reservoir of the LN$_2$ circulation system kept the circulation pump turned off, (iii) Exciting the compressor units by an AC power source with 45 Hz when the filling process ends, (iv) Increasing the input power in step-wise to prevent the piston from exceeding the allowable stroke during the cold-ends completely cooled down, (v) Circulating LN$_2$ from the internal reservoir to the entire system when the cold-ends reached to be below 77 K, (vi) Increasing the mass flow rate of LN$_2$ and the heat load as the input power supplied to the compressors elevated, (vii) Repeating the process (vi) until the steady-state temperature is obtained.

Figs. 3(a) and (b) depict the temperatures of eight cold-ends and the pipelines connected to the LN$_2$ circulation system, respectively. Each locus of the sensors are also described in the figures. Silicon diode (DT-670A, Lakeshore) sensors were utilized for all the temperature measurements and they were conditioned with temperature monitors (Model 218, Lakeshore). Fig. 3(c) illustrates the input power fed to the compressor units. Power analysers (WT1800, Yokogawa) were used for measuring the input power.

Figure 4. (a) Temperature distributions of the cold-ends (average value) and the both entrances of the LN$_2$ circulation system (b) the LN$_2$ mass flow rate and the corresponding heat load supplied to the cold-ends and (c) the input power of the Stirling cryocooler
3.2. Experimental results

The compressors adopt a moving magnet configuration and they recorded the compression efficiency (electrical to mechanical efficiency) to exceed 70% at all the experiment conditions. It had been measured solely prior to the integrated test described in this paper. Presently, our team is preparing a research paper that describes the thermal and dynamic characteristics of the developed Stirling cryocooler, so that the relevant details will be presented in near future. During the cool-down process, input power has been manually controlled to prevent the pistons collide on compressor’s body. Approximately an hour had been taken to reach the target temperature of 77 K. Once the temperatures are stabilized, LN\textsubscript{2} stored in the internal reservoir begins to be forced to the cold-ends. Fig. 4(a) represents all the average temperatures used in evaluating the cooling performance of the Stirling cryocooler system. The cooling capacity of the system has been evaluated by calculating enthalpy difference at the both entrances of the LN\textsubscript{2} circulation system, as (1). The thermodynamic data has been obtained from REFPROP 9.1 (NIST).

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Q = \dot{m}_{LN2} c_p A T = \dot{m}_{LN2} c_p (T_{LN2, in} - T_{LN2, out})
\]  

(1)

Figs. 4(b) and (c) show the resultant cooling capacity with the instantaneous mass flow rate of LN\textsubscript{2} and the input power, respectively. At the steady-state (205–215 min.), the system can produce the cooling power of 4.05 kW at the cold-end temperature of 77 K. The Carnot efficiency was recorded to be 28.4% with the input power of 41.2 kW. The heat load makes the temperature differences of 4 K at the both entrance and so the system is capable of sub-cooling of LN\textsubscript{2} at a thermal resistance of 1 kW/K.

4. Conclusions

Thus far, we have constructed and tested a Stirling cryocooler system in conjunction with a superconducting cable demonstration facility. The main features of the integrated system are as below,

(i) Introducing high capacity dual-acting linear compressor units: It is advantageous that there is no maintenance service involved for oil replacement and is intrinsically efficient (electric to mechanical conversion). The developed compressor units have recorded to exceed 70% conversion efficiency.

(ii) Adapting gamma-type free-piston configuration: The free-piston displacer as an expansion device moves freely without any mechanical linkage, so that it also can contribute on improving the system’s efficiency. The developed Stirling cryocooler system have recorded to exceed 28.4% Carnot efficiency.

(iii) Demonstrating that the cooling system works for a long-distance superconducting cable with 4.05 kW heat load at 41.2 kW-input power

The integrated cooling system, therefore, can readily replace a conventional crank-type Stirling cryocooler.

References

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