Progress in Development of High Capacity Stirling Cryocooler Using a Linear Compressor

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ABSTRACT

A high capacity Stirling cryocooler is being developed for HTS electric power devices. The developed cryocooler is driven by a dual-opposed type linear compressor and has gamma-type configuration. The first prototype was fabricated and tested and the results of the cooling performance tests were presented at CEC 2015. In this study, a modified prototype is fabricated to improve its cooling performance. The thrust constant of a linear motor is increased and a regenerator material is changed from screen mesh to random fiber.

In the cooling performance tests, the cold head temperature is measured at varying heat loads with a fixed input current. The results show a no-load temperature of 43.3 K, a cooling capacity of 650 W at 76.8 K with 8.76 kW electric power input and 21.6 % of Carnot COP. Turn down performance is also measured by adjusting input voltage for a fixed cold head temperature.

INTRODUCTION

High Temperature Superconductor (HTS) electric power devices such as HTS cables and HTS Fault Current Limiter (HTS-FCL) are undergoing field testing after the R&D phase in Korea[1-3]. They are expected to be commercialized in the near future, and a reliable and efficient high capacity cryocooler is indispensable for their commercialization. A crank-driven type Stirling cryocooler is commonly used for some kW class cryogenic cooling systems. It is commercially available and technically matured but, still has problems of vibration and frequent maintenance due to a crank-cam driving mechanism and the use of lubricating oil. A Stirling cryocooler driven by a dual-opposed linear compressor can solve these problems because it has the advantage of oil-free operation and is inherently vibration-free.

Previously, we fabricated and tested the first prototype of the high capacity Stirling cryocooler driven by the linear compressor. The experimental results showed a no-load temperature of 47.8 K, a cooling capacity of 440 W at 78.1 K with 6.45 kW of electric power input and 19.4 % of Carnot COP[4]. In this study, we modify the first prototype to improve the cooling performance. The dynamic behavior, the symmetric characteristics due to use of two linear motors, the cooling capacity and the efficiency are investigated from the cooling performance tests when the input current to a cryocooler is fixed. The variation of the cooling performance is measured from a turn down operation with a fixed cold head temperature.

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FABRICATION AND EXPERIMENTAL SETUP

The stator of the first prototype had a 260 coil turns. Its thrust characteristic is designed to have 6 kW input power at 60 Hz operation. We changed the operating frequency to 45 Hz after the performance test of the first prototype. Coil turns were increased to 292 turns to increase the thrust constant without a change to the dimension of the linear motor.

The regenerator has dimensions of 86, 130, and 80 mm for the inner diameter, outer diameter and length, respectively. A random fiber of SS 316L is used as the regenerator material instead of a stainless steel screen mesh in the modified cryocooler. The cold-end and the warm-end heat exchangers have a slit-type configuration and the heat is rejected by cooling water at warm-end heat exchanger. Figure 1 shows the modified cryocooler and the installation of heaters and temperature sensors at the cold head. To apply a heat load and to measure the spatial temperature distribution, 24 cartridge heaters of 50 W(Lakeshore, HTR-50) are uniformly inserted and 8 temperature sensors (Lakeshore, DT-670A-CU) are attached.

Figure 2 shows the electric connection for driving the cryocooler and measurements during tests. Two linear motors are electrically connected in parallel and an AC power supply (EXTECH, 6530) supplies electric power to the linear compressor. A resonant capacitor is connected between the AC power supply and each linear motor for power factor correction. Several capacitors are used to satisfy the desired capacitance and to withstand the voltage. Voltage, current, power and power factor are measured with the power analyzer (Yokogawa, WT1800). Electric heat is supplied by an AC power supply (Chroma, 61504) for the heat load tests. Accelerometers(PCB, 353B18) are attached to the piston and the displacer inside the cryocooler and the measured acceleration is con-

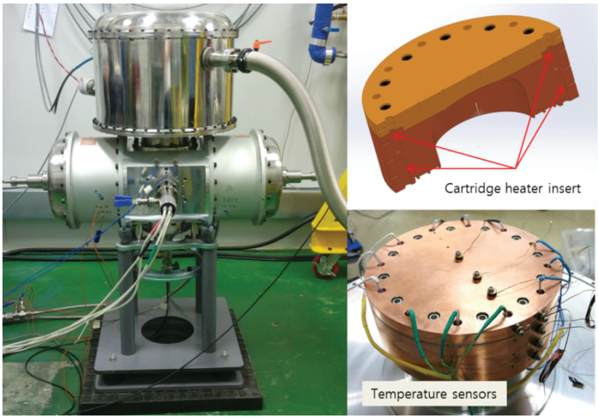

Figure 1. Photo of fabricated Stirling cryocooler and cold-head.

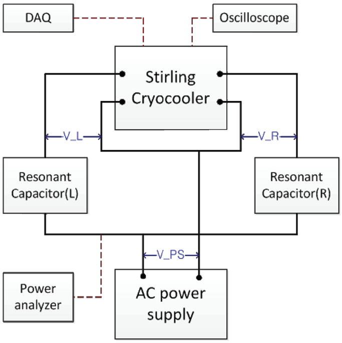

Figure 2. Schematic diagram of driving circuit and measurement.

verted to a displacement. Dynamic pressure sensors (PCB, 112A21) are installed to measure the dynamic pressure in the compression space. Waveforms for the acceleration, the dynamic pressure, the input current and the voltage are recorded to the oscilloscope (Yokogawa, DLM4038).

EXPERIMENTAL RESULTS

Cooling Performance Test

In the cooling performance test, the input voltage to the cryocooler is adjusted to a fixed input current of 36.7Arms. Figure 3 shows the measured cold head temperature of each point at steady state. The temperature deviation from the eight (8) spatially distributed sensors are within 1 K for all cases. Input voltage and power factor measured at the AC power supply (V_PS) and each linear motor (V_L, V_R) are shown in Figure 4. Driving voltage gradually increases with increasing cold head temperature. Voltage at the linear motor is higher than at AC power supply. The voltage difference between the two linear motors is less than 5 %. The power factor at the AC power supply is nearly 1.0, whereas value at linear motor is close to 0.35, which confirms that the resonant capacitor worked well.

Figure 5 and 6 show the displacement of piston and displacer and dynamic pressure in the compression space. Amplitude of piston, displacer and compression space pressure decrease as decreasing cold head temperature. The phase difference between input current and piston displacement(ϕ_{ixp}) decreases slightly as the cold head temperature increases. However, the phase difference between displacer and piston displacement(ϕ_{xdxp}) is almost constant. The phase difference between the pressure and the piston displacement(ϕ_{Pxp}) decreases as the cold head temperature increases. It means that the gas spring effect becomes stronger rather than gas damping effect with increasing cold head temperature.

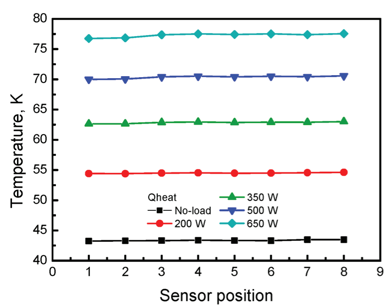

Figure 3. Spatial distribution of cold head temperature.

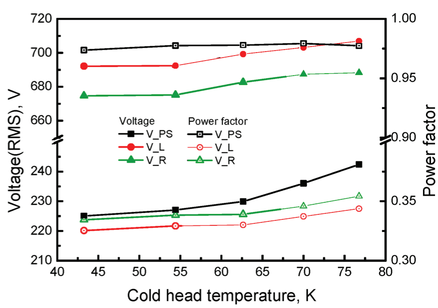

Figure 4. Voltage and power factor in driving circuit

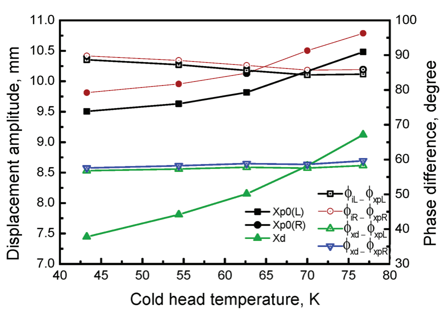

Figure 5. Displacement of piston and displacer.

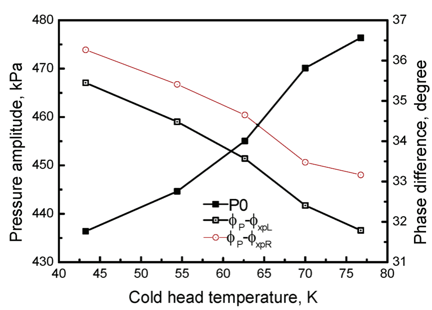

Figure 6. Pressure at compression space.

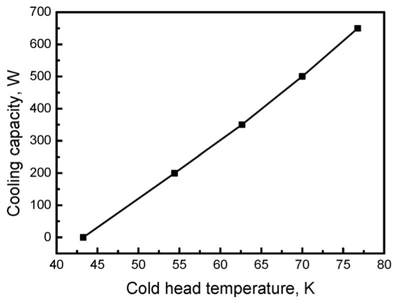

Figure 7. Cooling capacity.

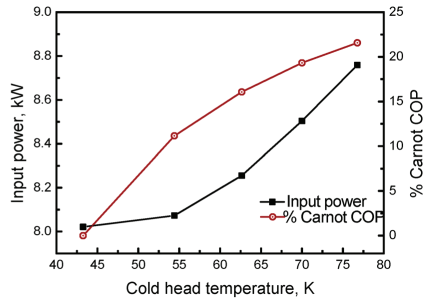

Figure 8. Input power and % Carnot COP.

Figure 7 and 8 show the measured the cooling capacity, the input power and the efficiency of the developed cryocooler. The no-load temperature is 43.4 K and the cooling capacity is 650 W at 76.8 K with 8.76 kW electric power input. The input power and % Carnot COP increases as cold head temperature increase.

Turn Down Operation

A turn down performance is informative to a cryocooler user. The developed cryocooler is tested with varying input voltages at a fixed cold head temperature of 77.9 K. To investigate the applicability to an LNG re-liquefaction system, the test is carried out at a cold head temperature of 110 K without any modification. Figure 9 and 10 show the results of the turn down operation. It measured a cooling capacity of 533 W with 3.33 kW of electric input power and 27.7 % of Carnot COP at 110 K operation. At that condition, the input voltage and current is 170 V and 19.7 Arms value, respectively. Figure 10 shows a decrease in efficiency with the turn down operation.

SUMMARY

In this study, the previously developed high capacity Stirling cryocooler driven by a linear compressor was modified to improve the cooling performance. Dynamic and electric symmetry are confirmed from the experimental results. The results of the cooling performance test with a fixed input current show a no-load temperature of 43.3 K, a cooling capacity of 650 W at 76.8 K with 8.76 kW electric power input and 21.6 % of Carnot COP. The turn down test was run while the cold head temperature is maintained at 77.9 K and 110 K to demonstrate the applicability to LNG re-liquefaction and HTS. The developed cryocooler is applicable to LN_2 cooling for HTS devices and also LNG re-liquefaction.

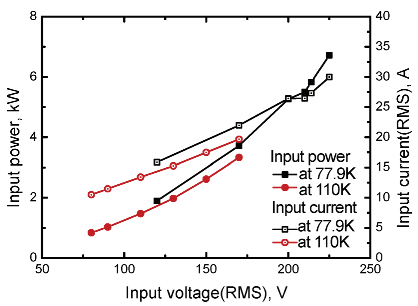

Figure 9. Turn down operation: input power and current.

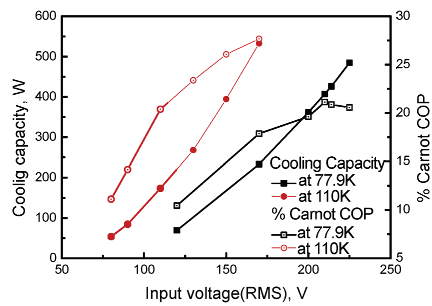

Figure 10. Turn down operation: cooling capacity and efficiency.

ACKNOWLEDGMENT

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