

Development of 1 kW Stirling cryocooler using a linear compressor

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Abstract. Cryogenic cooling systems for HTS electric power devices require a reliable and efficient high-capacity cryocooler. A Stirling cryocooler with a linear compressor can be a good candidate. It has advantages of low vibration and long maintenance cycle compared with a kinematic-driven Stirling cryocooler. In this study, we developed a dual-opposed linear compressor of 12 kW electric input power with two 6 kW linear motors. Electrical performance of the fabricated linear compressor is verified by experimental measurement of thrust constant. The developed Stirling cryocooler has a gamma-type configuration. The piston and displacer are supported with a flexure spring. A slit-type heat exchanger is adopted for the cold and warm-end, and the generated heat is rejected by cooling water. In the cooling performance test, waveforms of voltage, current, displacement and pressure are obtained and their amplitude and phase difference are analysed. The developed cryocooler reaches 47.8 K within 23.4 min. with no-load. Heat load tests shows a cooling capacity of 440 W at 78.1 K with 6.45 kW of electric input power and 19.4 of % Carnot COP.

1. Introduction

Several kinds of HTS electric power devices such as HTS cable and HTS-FCL are in progress of field testing after as R&D phase in Korea [1-3]. Such devices require a reliable and efficient high-capacity cryocooler and a crank-driven type Stirling cryocooler is widely used. It is commercialized and technically matured but, still has problems of vibration and frequent maintenance due to its use of lubrication oil. For the commercialization of HTS power devices, a reliable cryocooler is essential and a Stirling cryocooler driven by a linear compressor can be a good candidate.

In this study, we developed the gamma-type Stirling cryocooler driven by a dual-opposed linear compressor which has the advantages of being oil-free and inherently vibration-free. We first designed a linear compressor with consideration of its dynamic behavior and electromagnetic analysis. The electrical characteristics of the fabricated linear compressor is experimentally verified. If the designed dynamic behavior is satisfied, the fabricated linear compressor can transfer the rated electric power to the cryocooler. In experiments, the waveforms of several variables such as the piston/displacer displacement and pressure at the compression space are measured and the dynamic behaviors of the cryocooler are discussed. The cooling performance test is carried out to measure no-load temperature, cool-down time, cooling capacity, and % Carnot COP.



2. Design and fabrication

2.1. Linear compressor

We designed a linear compressor with 12 kW of input electric power at 60 Hz operation. It is a dual-opposed type and each piston is driven by a 6 kW linear motor. The rated voltage and current of the designed 6 kW linear motor are 380 V_{rms}(1 Φ) and 15.8 Arms, respectively. The designed values of piston diameter, stroke and thrust constant are 100 mm, 30 mm, and 85.5 N/A, respectively.

The performance of the fabricated linear motor was verified by measuring the thrust constant. We oscillated the moving parts with a fixed stroke and frequency. The two coil-ends of the stator are connected to an oscilloscope which has an infinite impedance. And then, the induced voltage is directly proportional to the velocity of the piston because the current is nearly zero due to its infinite impedance. If the mover is excited with a sinusoidal motion, the induced voltage is also sinusoidal. Then, the thrust constant is calculated with the following equation. Here, V_0 is the amplitude of the induced voltage, ω is the angular velocity of the mover, X_0 is the displacement amplitude and K_E is the thrust constant. Figure 1 shows an example waveform of the induced voltage.

$$V_0 = \omega K_E X_0 \quad (1)$$

The fabricated stator of the linear motor has three different coil turns of 240, 250, 260. The measured thrust constant agrees well with the analysis results as shown in figure 2. The results of figure 2 were obtained from the test at room temperature. However, the inside temperature of the linear compressor increases during the cryocooler operation due to the heat generation by electrical and mechanical loss [4]. It results in a degradation of the magnetic performance and thus a reduction of the thrust constant. We assumed a 10 % decrease of the thrust constant, and selected 260 coil turns of the stator for the fabricated prototype. Two linear motors are electrically connected in parallel.

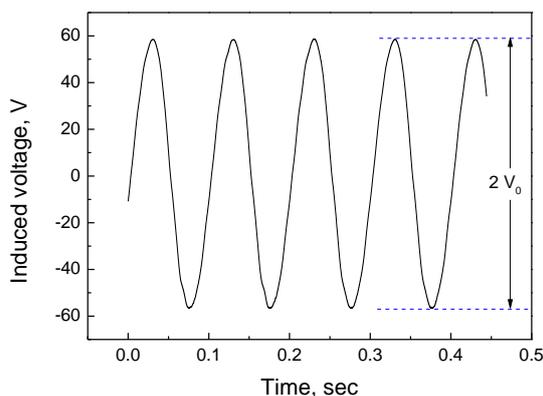


Figure 1. Measurement of induced voltage on the stator with an excitation of the mover for the fabricated linear motor.

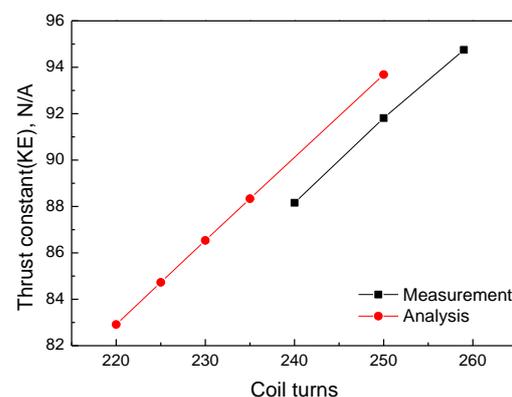


Figure 2. Comparison of measurement and analysis: thrust constant of the linear motor.

2.2. Cold part

The developed Stirling cryocooler in this research has a gamma-type configuration. The displacer is supported by a flexure spring and driven by the pressure difference between the compression and expansion spaces. The diameter and designed stroke of the displacer are 83 and 24 mm, respectively. The diameter of the connecting rod is 24 mm. The dimension of the regenerator is 86 mm inner diameter, 130 mm outer diameter and 80 mm length. A stainless steel screen mesh of #250 is used as

the regenerating material. Both heat exchangers of the cold and warm-end are fabricated with a slit-type configuration and the heat is rejected by cooling water at the warm-end heat exchanger. For applying a heat load and measuring spatial temperature distribution at the cold-head, 24 cartridge heaters of 50 W are inserted and 8 temperature sensors(Lakeshore, DT-670-CU) are installed as shown in figure 3. Figure 3 also shows the fabricated Stirling cryocooler. Its approximate size is 330, 820, 860 mm(Depth, Width, Height) and weight is less than 200 kg.

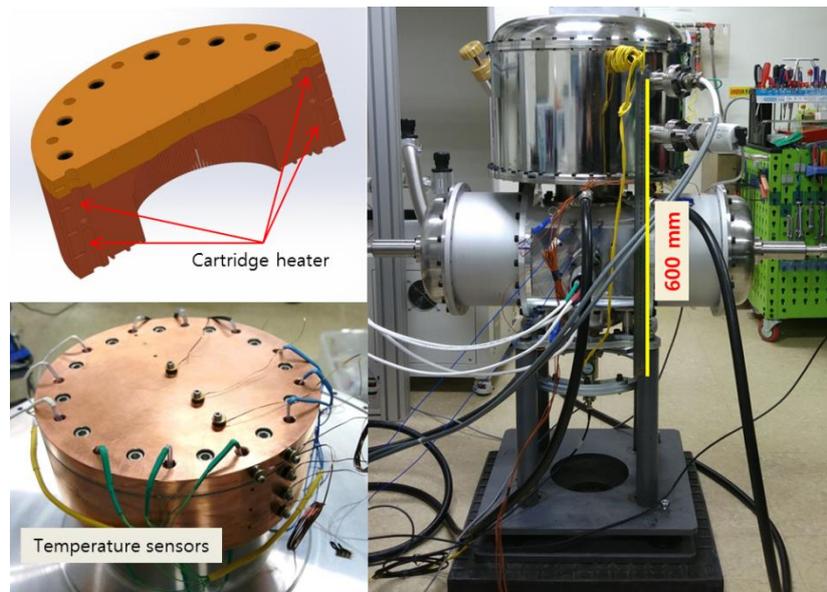


Figure 3. Photo of fabricated Stirling cryocooler and cold-head.

3. Cooling performance test

3.1. Experimental setup

Figure 4 shows the experimental setup for the cooling performance test. The linear compressor is driven by an AC power supply(EXTECH, 6530). The resonant capacitor set is used for power factor correction. Several commercial capacitors are used to satisfy the desired capacitance and voltage range. Voltage and current at each point of the driving circuit are measured with a power analyzer(Yokogawa, WT1800). Electric heat is supplied by an AC power supply(Chroma, 61504) for the heat load test. Accelerometers(PCB, 353B18) are attached to the piston and the displacer inside the cryocooler and the measured acceleration is converted to displacement. Dynamic pressure sensors(PCB, 112A21) are installed to measure the dynamic pressure in the compression space. Waveforms of acceleration, dynamic pressure, input current and voltage are recorded by the oscilloscope.

3.2. Experimental results

In the experiment, we slowly increase the input current from 0 to 31 Arms during the cool-down test with no heat load and the voltage is adjusted to maintain the input current of 31 Arms during the heat load test.

Figure 5 shows the measured cold-head temperature. The temperature deviation from the spatially distributed 8 temperature sensors is within 1 K at all cases of steady state. The cryocooler cools down to 47.8 K and the cool-down time is 23.4 min. During the heat load test, 100, 200, 300, 400, 440 W of heat is loaded to the cold-head and the cooling capacity line is obtained as shown in figure 6. The cold-head temperature proportionally increases with the increasing heat load and 440 W at 78.1 K is achieved with 6.45 kW of the input electric power. Figure 7 shows the variation of input power and % Carnot COP.

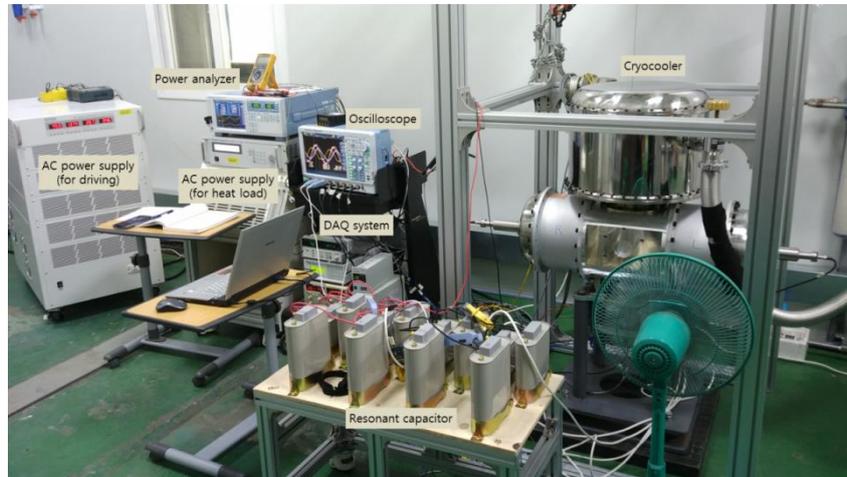


Figure 4. Photo of experimental setup.

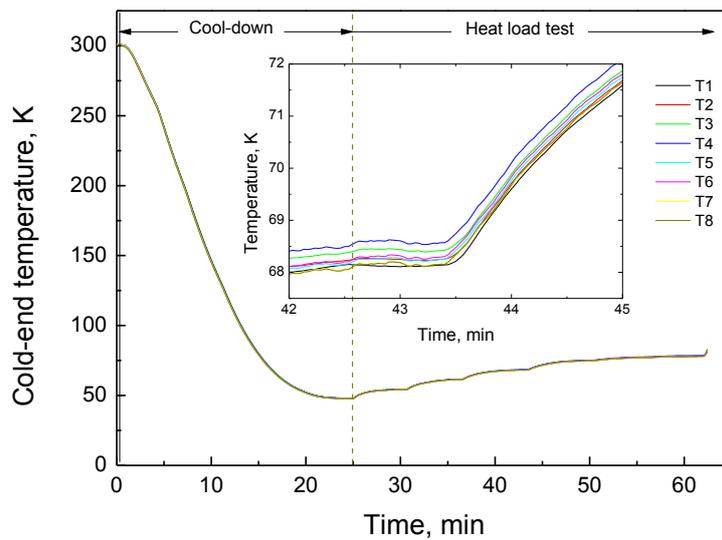


Figure 5. Cold-head temperature.

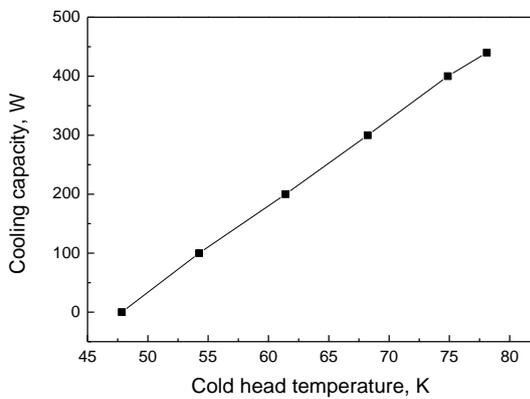


Figure 6. Cooling capacity.

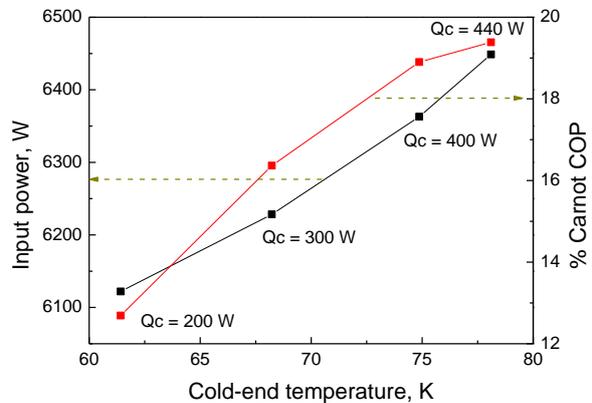


Figure 7. Input electric power and COP.

3.3. Experimental results

Figure 8 shows an example of the measured waveforms of displacement, dynamic pressure and input current. Here, all waveforms are almost sinusoidal and thus, the displacement is converted from the measurement of acceleration. From the measurement of waveforms, the amplitude and phase shift of all variables are obtained by fitting waveforms to the sine curve. The waveforms of the symmetrically assembled two linear motors are almost identical. The symmetry of the fabricated dual-opposed linear compressor is confirmed.

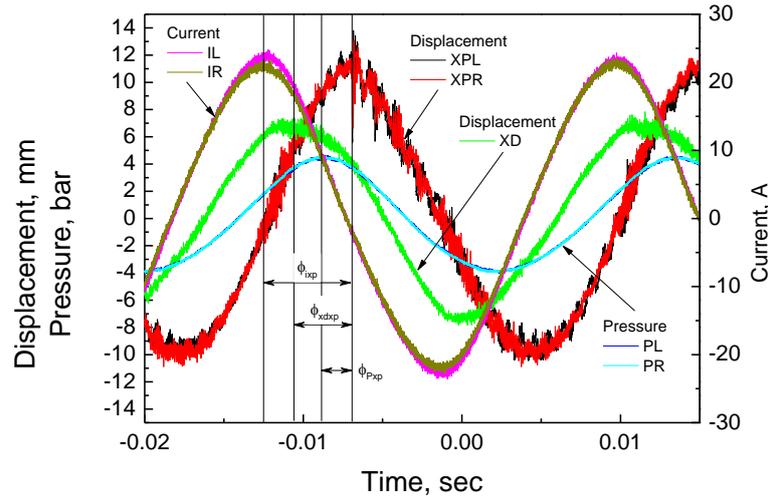


Figure 8. Measurement of waveforms.

Table 1. Fit and calculated data of waveforms.

Qc	Tc	Xp0 (L/R)	Xd0	ϕ_{ixp} (L/R)	ϕ_{xdyp} (L/R)	P0 (L/R)	ϕ_{pxp} (L/R)	Input power	PV power	η_{comp}
W	K	mm	mm	degree	degree	kPa	degree	W	W	-
0	47.8	9.69/9.89	6.21	105/105	60	366/370	36/36	6258	4668	0.746
100	54.3	9.73/9.95	6.41	102/103	61	376/379	35/35	6334	4730	0.747
200	61.4	9.64/9.85	6.51	100/101	62	379/382	34/34	6122	4624	0.755
300	68.2	9.66/9.89	6.68	98/99	62	386/390	33/33	6228	4626	0.743
400	74.9	9.82/10.04	6.92	97/97	62	397/401	33/32	6363	4713	0.741
440	78.1	9.85/10.14	7.03	95/95	62	407/410	32/32	6449	4783	0.742

Qc : Cooling capacity

Tc : Cold-end temperature

Xp0 : Amplitude of piston displacement

Xd0 : Amplitude of displacer displacement

L/R : Left side / Right side

Φ_{ixp} : Phase shift b/w current and piston displacement

Φ_{xdyp} : Phase shift b/w displacer and piston displacement

Φ_{pxp} : Phase shift b/w pressure and piston displacement

P0 : Pressure amplitude at compression space

η_{comp} : Compressor efficiency

The sinusoidal curve fit data and calculated compressor efficiency at varying heat load are shown in Table 1. The phase difference between the input current and piston displacement (ϕ_{ixp}) is 95 ~ 105°. It confirms the resonant operation of the linear compressor. The phase difference between displacer

and piston($\phi_{x,dp}$) is $60 \sim 62^\circ$ which is close to the design value. The measured phase differences agree well with the design values, but the displacement of the piston and displacer are smaller than that. It is guessed that the small displacement of the displacer is due to an excessive pressure drop through the regenerator. In the next prototype, the regenerator will be modified to reduce the pressure loss.

With the measured piston displacement and dynamic pressure, the compression PV power is calculated and the compressor efficiency is around 75 % for all cases.

4. Summary

In this research, we developed a gamma-type Stirling cryocooler driven by a dual-opposed linear compressor. The performance of the fabricated linear compressor is verified by measuring the thrust constant. In the cooling performance test, the waveforms of displacement, pressure and electric input are measured and the dynamic behaviour is discussed. The compression PV power is calculated with the measured piston displacement and dynamic pressure, and the compressor efficiency is around 75 %. The fabricated Stirling cryocooler reaches 47.8 K within 23.4 min. with no-load. It has 440 W of cooling capacity at 78.1 K and operates at 19.4 % of Carnot COP with 6.45 kW of input electric power.

Acknowledgments

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