

Experimental Research on Piston Offset and Performance of a High-Efficiency Moving Coil Linear Compressor for J-T Throttle Refrigerator

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ABSTRACT

In order to improve the efficiency of a J-T throttling refrigerator, a high-efficiency moving coil linear compressor (scavenge volume 5.84 cm³) was developed. In order to evaluate its performance, the linear compressor prototype was tested with nitrogen as a working fluid at different pressure ratios (2.0/2.5/3.0/3.5), different strokes (6-11 mm), and different driving frequencies (55-67.5 Hz). Key performance parameters such as the mass flow rate, motor efficiency, volumetric efficiency, isentropic efficiency and isothermal efficiency have been obtained. In addition, the specific parameters of the linear compressor (such as piston offset and resonance frequency) have also been studied. At the design point the, pressure ratio is 3, stroke is 10 mm, frequency is 65 Hz, the input power is 151.2 W, the mass flow rate is 0.84 gr/s, the motor efficiency is 86.3%, the volumetric efficiency is 75.5%, the isentropic efficiency is 64.1%, and the isothermal efficiency is 54.5%. When the pressure ratio is 3, the stroke is 11 mm, and the frequency is 67.5 Hz, the maximum mass flow rate is 1.038 gr/s, and the input power is 191.7 W. This experiment can provide an important reference for other operating conditions (such as other pressure ratios and working fluids).

INTRODUCTION

The pre-cooling J-T throttling refrigerator has the advantages of stable operation, low vibration, strong electromagnetic resistance, and relatively high efficiency at liquid helium temperature, which has always been the research hotspot in the field of cryogenic mechanical refrigerators¹ such as: James Webb Space Telescope (NASA)²⁻⁴, Astro-H and SPICA space exploration mission (JAXA/ESA/NASA)⁵⁻⁷. As the core component of the J-T throttling refrigerator, the linear compressor provides the pressure ratio and flow rate required by the throttling cycle. Therefore, improving performance of the linear compressor is very important to improve efficiency of the throttling system.

In order to meet the requirements of Astro-H and SPICA detection tasks, Sumitomo Heavy Industries developed a linear compressor supported by the flexure springs. The mass flow rate was 8.66 mg/s and the input power was 55.9 W under the conditions of suction pressure of 1.21 bar, discharge pressure of 19.99 bar and pressure ratio of 16.5, in addition, with He3 as the working fluid and through the form of 4-stage compression, the system reached the working condition with the suction pressure of 0.08 bar and the discharge pressure of 7 bar⁸⁻⁹. In China, the pressure ratio of the

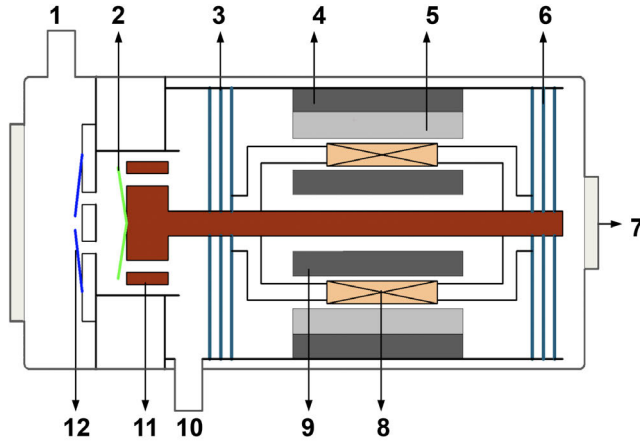


Figure 1. Schematic diagram of linear compressor structure: 1 discharge outlet, 2 suction valve, 3 flexure spring, 4 outer core, 5 permanent magnet, 6 flexure spring, 7 glass visualization window, 8 copper coil, 9 inner core, 10 suction inlet, 11 piston, 12 discharge valve.

linear compressor independently designed by Zhejiang University has reached 1.37¹⁰. In 2013, key Laboratory of Space Energy Conversion Technology, Technical Institute of Physics and Chemistry, CAS successfully developed a three-stage pulse tube pre-cooled throttle refrigerator adopting two-stage compression to obtain a pressure ratio of 7¹¹. In 2019, the laboratory reduced piston offset and improved performance of linear compressors by increasing the axial stiffness of the flexure springs. Through experimental optimization, the pressure ratio of the low-pressure stage linear compressor was increased from 2.8 to 4.5, and the high-pressure stage linear compressor was increased from 1.9 to 2.7. Finally, the two-stage pressure ratio was 11.8 when the input power was 65 W¹².

It can be seen that improving the pressure ratio, the mass flow rate and efficiency of the single-stage linear compressor for the J-T throttling refrigerator is always an important research hotspot. Our laboratory recently developed a high efficiency linear compressor. In order to evaluate its performance, the prototype was tested under different pressure ratios, piston strokes and frequencies to achieve the key parameters such as the mass flow rate, input power, motor efficiency, isentropic efficiency, isothermal efficiency, volumetric efficiency and piston offset.

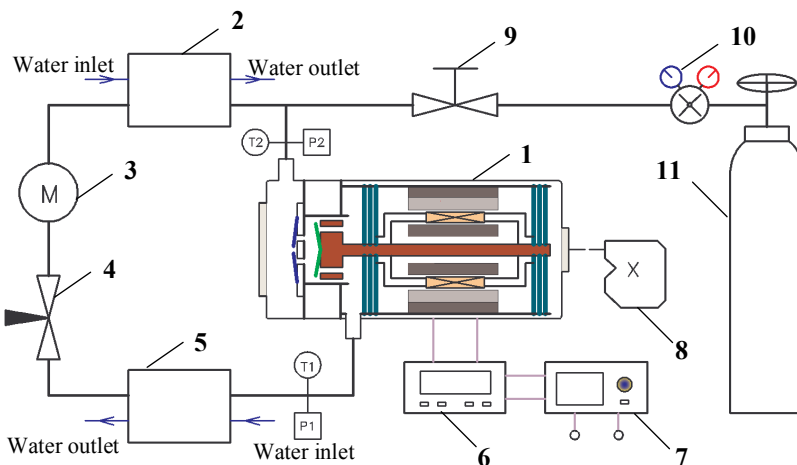


Figure 2. Test loop of the linear compressor: 1 linear compressor, 2 high pressure heat exchanger, 3 mass flow meter, 4 manual throttle valve, 5 low pressure heat exchanger, 6 power meter, 7 NF power supply, 8 laser displacement sensor, 9 manual diaphragm valve, 10 gas reduction pressure valve, 11 nitrogen cylinder.

Table 1. Linear compressor and system operating parameters.

| Parameters (unit) | Value |
|-------------------------------|------------------------------|
| Cylinder diameter (mm) | 26.0 |
| Compressor stroke (mm) | 7, 8, 9,10,11 |
| Operating frequency (Hz) | 55, 57.5, 60, 62.5, 65, 67.5 |
| Initial clearance length (mm) | 3.83 |
| Resistance (Ω) | 1.0 |
| Working fluid | N ₂ |
| Fill pressure (MPa) | 0.7 |
| Pressure ratio | 2.0, 2.5, 3.0, 3.5 |
| Suction pressure (bar) | 4.15, 3.38, 2.85, 2.47 |

EXPERIMENTAL APPARATUS

The prototype diagram of the moving coil linear compressor is shown in Figure 1. The permanent magnet adopts a radial magnetization structure and has 10 flexure springs with a high radial-to-axial stiffness ratio are installed on both sides of the linear motor to support the moving component and reduce the dry friction between piston and cylinder. A piston having a ring hollow increases the gas intake and reduce the suction loss. The valve plate with four holes increase the discharge capacity and reduce the discharge loss. In addition, the entire gas flow channel is optimized to reduce flow loss and heat transfer loss, and a lot of work was done to improve the performance of the linear compressor.

Figure 2. shows the schematic of the linear compressor test loop. The linear compressor is driven by the NF power supply, and its electrical parameters are collected and displayed by the power meter. The stroke and operating frequency of the linear compressor are respectively controlled by the voltage amplitude and frequency of the NF power supply. The pressure ratio of the system is changed by adjusting the opening of the manual throttle valve. A laser displacement sensor is installed to measure the stroke and offset of the piston, and the mass flow rate is measured by the Coriolis Mass Flowmeter. The linear compressor and system operating parameters are shown in Table 1.

RESULTS AND DISCUSSIONS

In order to evaluate the performance of the prototype, the performance of the linear compressor under different pressure ratios, different piston strokes and different frequencies was tested.

The Mass Flow Rate and Input Power

Figure 3 shows the mass flow rate and input power under variable piston stroke for 4 different pressure ratios at 65 Hz. It can be seen that the mass flow rate under different pressure ratios increases approximately linearly with the increasing stroke. When the stroke is 11 mm and the

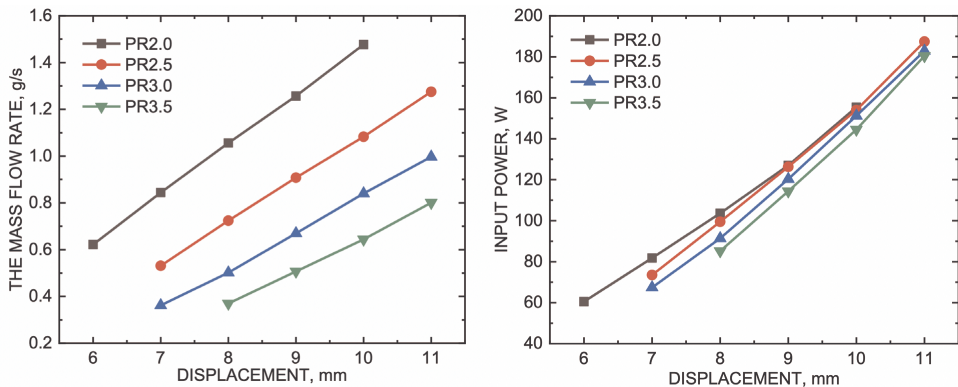


Figure 3. The mass flow rate and input power under variable piston stroke ($f=65$ Hz).

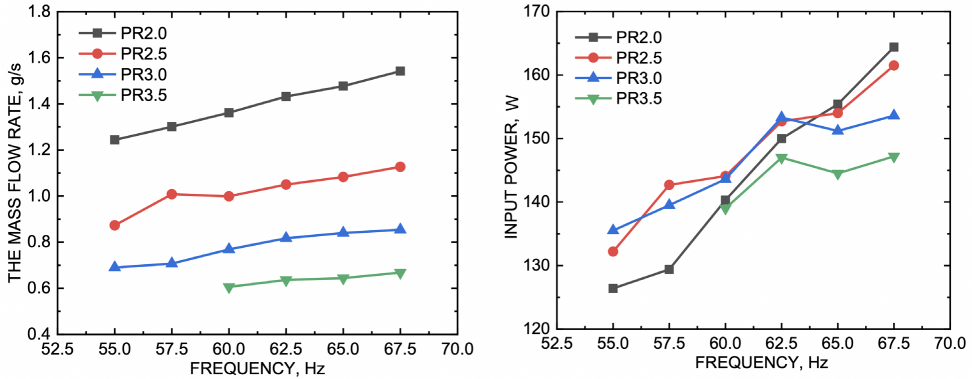


Figure 4. The mass flow rate and input power under variable drive frequency and stroke ($S=10$ mm).

pressure ratio is 3, the maximum mass flow rate is 1.0 gr/s at 65 Hz; the input power under different pressure ratios increases with an increasing stroke, and the gradient increases with an increasing pressure ratio. When the piston stroke is 11 mm, the input power under different pressure ratios is almost equal, the value is about 184 W.

Figure 4 shows the mass flow rate and input power under variable drive frequency for 4 different pressure ratios under 10 mm stroke. The mass flow rate under different pressure ratios increases approximately linearly with the increasing frequency, but the gradient decreases with an increasing pressure ratio. The input power under different pressure ratios increases with an increasing frequency, but the gradient decreases with an increasing compression ratio.

The Motor Efficiency, Isentropic Efficiency and Isothermal Efficiency

The motor power loss of a moving coil linear compressor is mainly joule heat generated by coil copper resistance. The motor efficiency can be calculated by Equation 1:

$$h_{motor} = 1 - \frac{I_{rms}^2 R}{\dot{W}_{in}} \quad (1)$$

where I_{rms} is the effective value of the drive current, R is the resistance of the copper coil, and \dot{W}_{in} is the input power.

The isentropic efficiency and isothermal efficiency of the linear compressor are obtained by equation 2 and equation 3:

$$h_{isen} = \frac{\dot{W}_{isen}}{\dot{W}_{in}} = \frac{k}{k-1} \dot{m}_0 R_g T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] / \dot{W}_{in} \quad (2)$$

$$h_{iso} = \frac{\dot{W}_{iso}}{\dot{W}_{in}} = \dot{m}_0 R_g T_1 \ln \left(\frac{P_2}{P_1} \right) / \dot{W}_{in} \quad (3)$$

where k is the isentropic coefficient ($k=1.4$ for N_2), \dot{m}_0 is the system mass flow, R_g is ratio of isobaric to isochoric specific heats, T_1 is the compressor suction temperature, P_2 is the discharge pressure, P_1 is the suction pressure.

Figure 5 shows the motor efficiency, isentropic efficiency and isothermal efficiency under variable piston stroke for 4 different pressure ratios at 65 Hz. It can be seen that the motor efficiency, isentropic efficiency and isothermal efficiency under the pressure ratios of 2.0 and 2.5 are all reduced with an increasing stroke, but the motor efficiency, isentropic efficiency and isothermal efficiency under the pressure ratios of 3.0 and 3.5 increase first and then decrease with an increasing stroke; this difference is caused by the different resonance frequencies of linear compressors at different pressure ratios and different strokes.

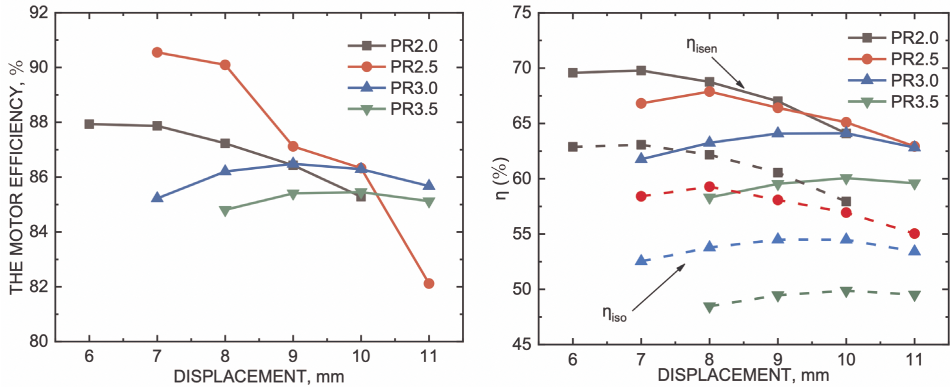


Figure 5. Motor, isentropic efficiency and isothermal efficiency under variable piston stroke ($f=65$ Hz).

Figure 6 shows the motor efficiency, isentropic efficiency and isothermal efficiency under variable drive frequency for 4 different pressure ratios with 10 mm stroke. As the frequency increases, the motor efficiency, isentropic efficiency, and isothermal efficiency under pressure ratios of 2.0 and 2.5 first increase and then decrease, while the motor efficiency, isentropic efficiency, and isothermal efficiency is always increasing under pressure ratios of 3.0 and 3.5. This is because the resonant frequencies of the pressure ratios 2.0 and 2.5 with a stroke of 10 mm are respectively 60.0 Hz and 65.0 Hz, but the resonant frequencies under the pressure ratios of 3.0 and 3.5 are both more than 67.5 Hz.

In summary, the maximum motor efficiency of the prototype under the pressure ratios of 2.0/2.5/3.0/3.5 is 87.9%, 90.6%, 86.6%, and 86.5%; the maximum isentropic efficiency is 69.8%, 67.9%, 64.1% and 61.1%; the maximum isothermal efficiency is 63.1%, 59.3%, 54.5% and 49.9%.

Piston Offset and Volumetric Efficiency

The piston of the valved linear compressor will be offset due to the unequal gas force at the front and back of the piston. Piston offset can affect clearance volume and volume efficiency.

The volumetric efficiency of the linear compressor can be obtained by Equation 4:

$$h_v = \frac{\dot{m}_0}{\dot{m}_{theory}} = \frac{4\dot{m}_0 R_g T_1}{\rho D^2 S f P_1} \tag{4}$$

where D is the piston diameter, S is the piston stroke, and f is the drive frequency.

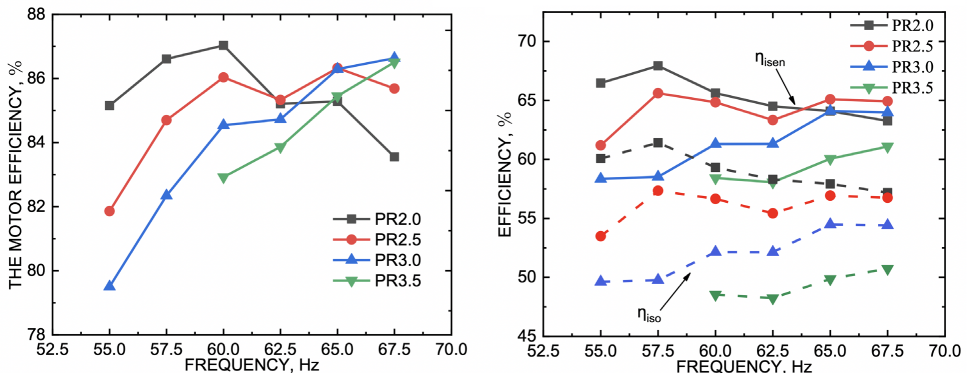


Figure 6. Motor efficiency, isentropic efficiency and isothermal efficiency under variable drive frequency and stroke ($S=10$ mm).

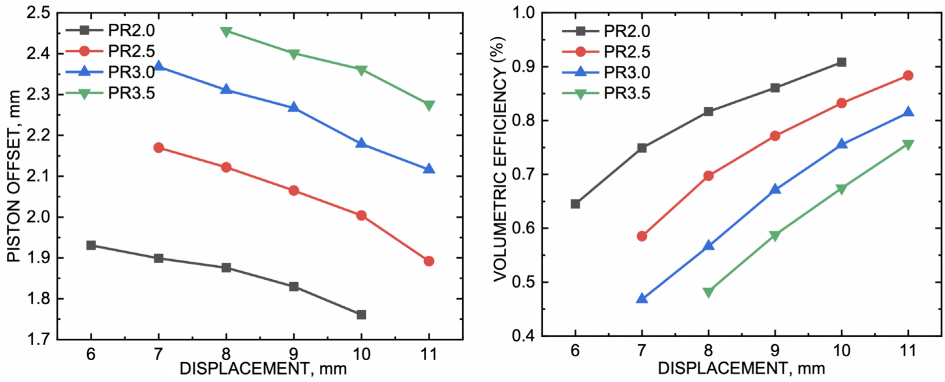


Figure 7. Piston offset toward the motor and volumetric efficiency under variable piston stroke ($f=65$ Hz).

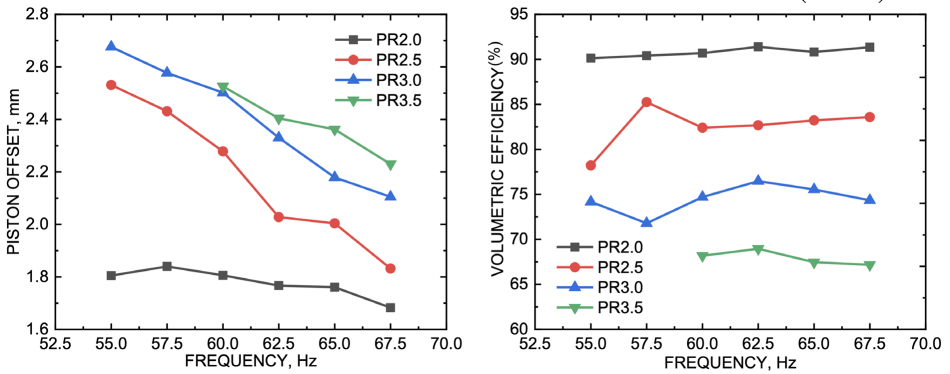


Figure 8. Piston offset toward the motor and volumetric efficiency under variable driving frequency and stroke ($S=10$ mm).

Figure 7 shows the piston offset and volumetric efficiency with different piston strokes for 4 different pressure ratios at 65 Hz. It can be seen that the piston of the linear compressor will offset toward the motor, and the value will decrease as the stroke increases and the pressure ratio decreases. This is because the average gas pressure in the cylinder decreases with the increase of stroke, the pressure difference between the front and rear of the piston decreases, and the total gas force on the piston decreases, so the piston offset decreases. When the pressure ratio increases, the gas pressure difference between the cylinder and the back pressure chamber increases, the total gas force on the piston increases, and the piston offset increases. The volumetric efficiency of the linear compressor increases with the increase of the stroke and the decrease of the pressure ratio. At the drive frequency of 65 Hz, the maximum volumetric efficiency of the pressure ratios of 2.5/3.0/3.5 is achieved with a stroke of 11 mm is 88.4%, 81.5%, and 75.7%.

Figure 8 shows the piston displacement and volumetric efficiency of the linear compressor under different driving frequencies for 4 different pressure ratios with a 10 mm stroke. It can be seen that the displacement of the piston decreases with the increase of the frequency, while the volumetric efficiency is almost constant with frequency.

CONCLUSION

The mass flow rate of the linear compressor prototype under different pressure ratios increases approximately linearly with the increase of piston stroke and driving frequency. When the pressure ratio is 3, the gradient of the mass flow rate is 160.8 mg/s/mm and 14.5 mg/s/Hz, the maximum mass flow rate is 1.0 gr/s at 65 Hz and 11 mm, and the input power is 183 W.

The excellent and reasonable structure design of the linear compressor brings high efficiency. The maximum motor efficiency under the pressure ratios of 2.0/2.5/3.0/3.5 is 87.9%, 90.6%, 86.6% and 86.5%;

the maximum isentropic efficiency is 69.8%, 67.9%, 64.1% and 61.1%; the maximum isothermal efficiency is 63.1%, 59.3%, 54.5% and 49.9%.

The structure of the linear compressor causes the piston offset toward the motor. The piston offset decreases with the increase of stroke and frequency, but it increases with an increasing pressure ratio. The volumetric efficiency will increase significantly with an increasing the stroke, but it will change little with the increasing frequency. At a drive frequency of 65 Hz and a pressure ratios of 2.5/3.0/3.5, the maximum volumetric efficiencies are achieved when the stroke is 11 mm, which are 88.4%, 81.5%, 75.7%, respectively.

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