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Theoretical and Experimental Investigation on Comparing the Efficiency of a Single-Piston Valved Linear Compressor and a Symmetrical Dual-Piston Valved Linear Compressor

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Abstract: The efficiency of the valved linear compressor is very important to the efficiency of the space J-T throttling refrigerator. To compare the efficiency of the single-piston valved linear compressor (SVLC) and the symmetrical dual-piston valved linear compressor (SDVLC), this paper explores the factors that affect efficiency. Firstly, this paper analyzes the mechanical vibration system of the linear compressor, the result shows that the efficiency is highest when the external force (current) is in phase with the speed. Then the numerical solutions of the current and velocity are obtained. By comparing the variance and same direction rate of the current and velocity between the SVLC and SDVLC, the reason for the difference in efficiency is explained. Subsequently, the performance of the SVLC and SDVLC are tested on the experimental system. The result shows that the current and velocity of the SDVLC are more in phase, and the isentropic efficiency, volume efficiency and motor efficiency of the SDVLC are all higher than that of the SVLC.

Keywords: linear compressor; efficiency research; mechanical vibration system

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1. Introduction

With the continuous development of space exploration, the cryogenic refrigerator for space detectors needs to seek a higher efficiency and lower minimum temperature [1–3]. Recently, linear compressors that provide a pressure ratio and mass flow for space cryogenic refrigerators have been studied. The linear compressor adopts the flexure spring support and gap sealing technology, which reduces the friction loss on the piston. Therefore, the mechanical efficiency of the compressor is improved, which is 20% higher than the overall efficiency of the traditional piston compressors [4].

The linear compressor can be divided into the valved linear compressor and the valveless linear compressor, which are respectively applied to different space refrigerator systems. Generally, valveless linear compressors are commonly applied to pulse tube refrigerators and Stirling refrigerators, while valved linear compressors are applied Joule–Thomson (J-T) throttling refrigerators [5–8]. Compared with the valveless linear compressors, valved linear compressors can establish a higher pressure ratio which is currently the research hotspot.

As an important moving and energy-consuming component of the cryocooler, the valved linear compressor affects the cooling capacity and efficiency of the refrigerator [9–11]. Consequently, it is extremely crucial to improve the efficiency of the valved linear compressor. Some scholars have made different explorations for the improvement of efficiency.

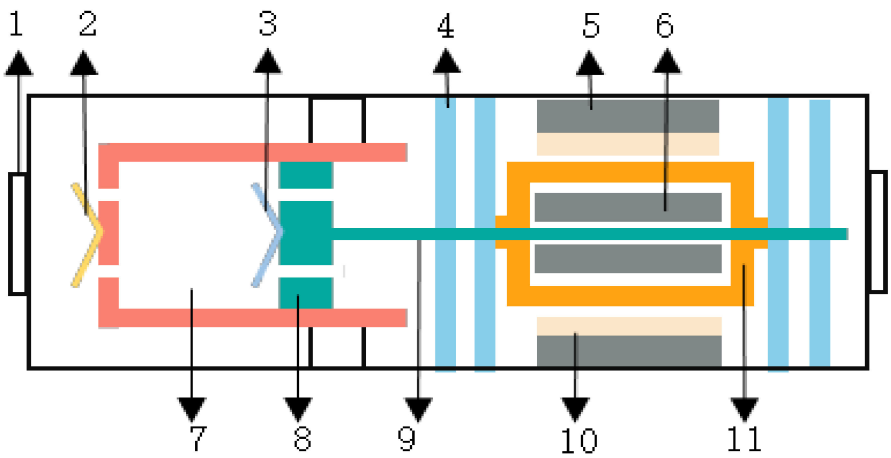
Firstly, the volume efficiency of the valved linear compressors could be improved by reducing the clearance volume. Hanying J et al. discovered that when the clearance is reduced from 0.8 mm to 0.6 mm, an averaged 4% increase in the experimental volumetric efficiency was achieved [12]. However, this method could cause the risk of the piston hitting the cylinder and make the assembly process more difficult.

When the piston of the linear compressor moves at full stroke, the offset will cause the pressure ratio, mass flow and motor efficiency to decrease [13]. Therefore, controlling the piston offset is also an approach to improve efficiency. Liang et al. [14,15] showed the methods of controlling the piston offset, which is increasing the stiffness ratio of the mechanical to gas springs, superimposing a DC voltage to limit the motion of the piston, and control of the pressure in the cylinder. Zou et al. [16] investigated the operating characteristics of the compressor under a different spring stiffness. It can be found that the spring stiffness had a significant impact on the compressor performance. Chen et al. illustrated that increasing the DC voltage can countervail the moving offset [17]. Nevertheless, the DC offset control method brings about an additional electrical power loss and extra Joule heat on the coil. Qi H et al. connected the suction line to the compressor shell which increases the compressor chamber pressure and reduces the pressure difference, to reduce the offset [18]. The approach could improve the motor efficiency, but will reduce the pressure ratio, in practice. In essence, the symmetrical dual-piston structure can minimize or even offset its own vibration [19]. Jian S et al. [20] describes that the dual piston system can significantly reduce the piston offset, in which the motor efficiency and volume efficiency are 87.9% and 79.1%. There is still insufficient research on the comparison of the efficiency between SVLCs and SDVLCs. Based on theory and experiment, this paper shows the difference in the volumetric efficiency, motor efficiency and isentropic efficiency in the valved linear compressors with different piston structures, respectively.

2. Structure and Working Principle of the Valved Linear Compressors

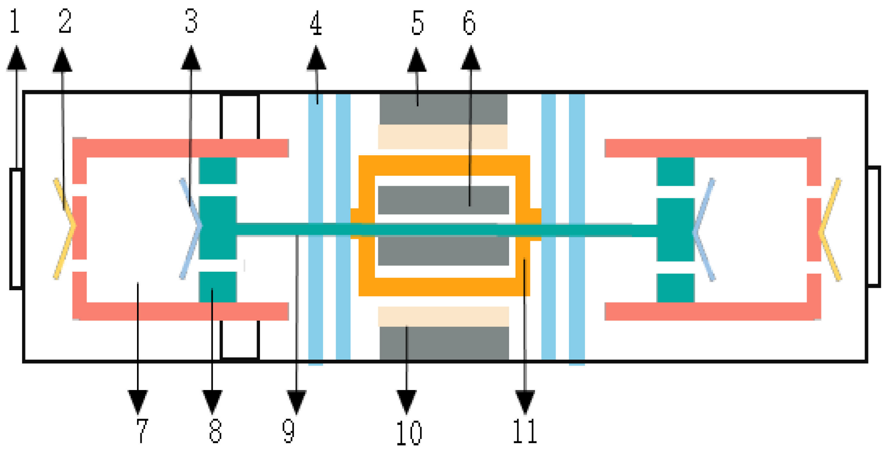
Figure 1 indicates the compositions of a SVLC and a SDVLC, respectively. They both include linear motors, flexure springs, cylinders, pistons, suction valves and discharge valves, etc. The linear motor is a moving coil structure, flexure springs support the coil and the piston to ensure the coaxiality of the cylinder. The discharge valves and the suction valves are arranged on the cylinders and the pistons. The reciprocating linear motor drives the piston to move in the cylinder and complete the compression and expansion process.

The difference between the two structures is that a coil drives a piston of the SVLC, and a coil drives two pistons of a dual-piston linear compressor. Two compression processes could be completed in one cycle of a dual-piston linear compressor, but that is only once of the SVLC.



(**a**)

Figure 1. *Cont.*

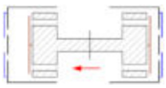
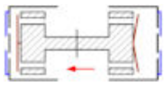
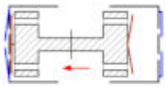
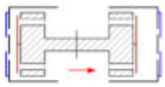
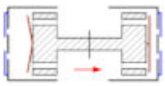
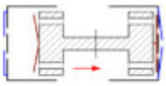


(**b**)

Figure 1. (**a**) the compositions of a SVLC; (**b**) the compositions of a SDVLC (1. sight window 2. discharge valve 3. suction valve 4. flexure spring 5. outer iron 6. inner iron 7. cylinder 8. piston 9. spindle 10. permanent magnet 11. coil).

The piston of the SDVLC reciprocates under the drive of the linear motor. The compression, discharge, expansion and suction processes are carried out, sequentially, in the cylinder. The suction valve and the discharge valve control the gas in and out of the cylinder. The working process illustration with the displacement direction is shown in Table 1. Due to the lack of one piston, the SVLC has a simpler working process than the SDVLC, and the gas is only compressed, discharged, expanded and suctioned in one cylinder.

Table 1. Working processes of the SDVLC.

Process	Piston Displacement	Left Cylinder	Right Cylinder
a		Compression	Expansion
b		Compression	Suction
c		Discharge	Suction
d		Expansion	Compression
e		Suction	Compression
f		Suction	Discharge

3. Theoretical Research on the Current and Velocity Characteristics

In addition to the gas force, the piston is subjected to an electromagnetic force during its motion. Due to the presence of friction losses, the system is mechanically damped. At the same time, the flexure springs also provide a reactive force during the motion of the piston. The gas force could be equivalent to a gas spring force, a gas damping and a static force. It should be noted that the static force does not exist in a SDVLC. Therefore, the whole linear compressor could be regarded as a single degree of freedom, damped forced vibration system [21]. The dynamics of the linear compressor are modelled as Figure 2.

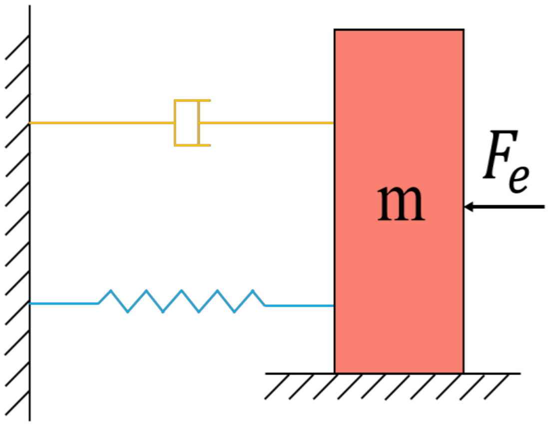


Figure 2. Schematic diagram of a single-degree-of-freedom, damped forced vibration system.

When the electromagnetic force $F_e = F_0 \sin \omega t$, its kinetic equation is:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t \tag{1}$$

Substitute the initial conditions: $x(0) = 0,\ \ x(\dot{o}) = 0$. Following the calculation, we could obtain the displacement:

$$x = e^{-\omega_n \xi t}(\mathrm{C}_1 \mathrm{cos}\omega_d t + \mathrm{C}_2 \mathrm{sin}\omega_d t) + X\mathrm{sin}(\omega t - \psi) \tag{2}$$

Obviously, the first term on the right side of the equation is the decay term, and the displacement response at the steady state is:

$$x = X\mathrm{sin}(\omega t - \psi) \tag{3}$$

The steady state response can be obtained by Equation (4):

$$x = X \sin(\omega t - \psi) = X \cos\left(\omega t - \psi - \frac{\pi}{2}\right) = Re\left[Xe^{j(\omega t - \psi - \frac{\pi}{2}}\right] \tag{4}$$

It could be the first derivative and second derivative by Equations (5) and (6):

$$\dot{x} = X\omega \cos(\omega t - \psi) = Re\left[X\omega e^{j(\omega t - \psi)}\right] \tag{5}$$

$$\ddot{x} = -X\omega^2 \sin(\omega t - \psi) = X\omega^2 \cos\left(\omega t - \psi + \frac{\pi}{2}\right) = Re\left[X\omega^2 e^{j(\omega t - \psi + \frac{\pi}{2})}\right] \tag{6}$$

In addition to the incentive force in the system, it is:

$$F = F_0 \sin \omega t = F_0 \cos\left(\omega t - \frac{\pi}{2}\right) = Re\left[F_0 e^{j(\omega t - \frac{\pi}{2})}\right] \tag{7}$$

There are also the following forces, namely the spring force F_k, damping force F_c and inertial force F_m, and equations are as follows:

$$F_k = -kx = -kX \cos\left(\omega t - \psi - \tfrac{\pi}{2}\right) = Re\left[-kXe^{j(\omega t - \psi - \frac{\pi}{2}}\right] \tag{8}$$

$$F_c = -c\dot{x} = -cX\omega \cos(\omega t - \psi) = Re\left[-cX\omega e^{(\omega t - \psi)}\right] \tag{9}$$

$$F_m = -m\ddot{x} = mX\omega^2 \cos\left(\omega t - \psi - \tfrac{\pi}{2}\right) = Re\left[mX\omega^2 e^{j(\omega t - \psi - \frac{\pi}{2})}\right] \tag{10}$$

The complex exponential form of the above quantities are shown in Figure 3. When the angular frequency is equal to the natural angular frequency of the system, which is $\omega\sqrt{\mathrm{k}/\mathrm{m}}$, the inertial force is equal to the spring force. The equilibrium could only be achieved if the electromagnetic force (incentive force F) is equal to the damping force F_c, the displacement lags the incentive force by 90°, at this time, the electromagnetic force and velocity are in phase. Because the electromagnetic force and the current are in phase, it illustrates that the efficiency is the highest when the current and the velocity are in phase.

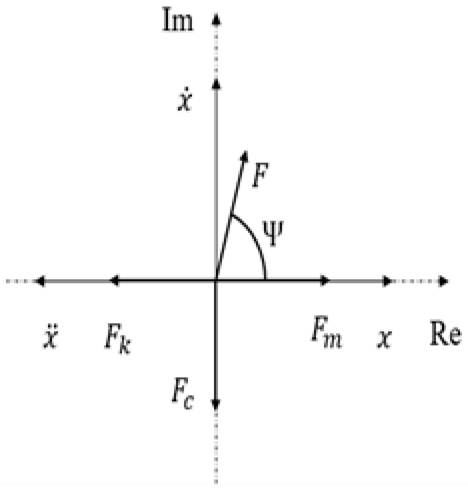


Figure 3. Schematic diagram of the force balance of the linear compressor mover.

When assuming:

(1) The mover displacement is sinusoidal $x = X\sin(\omega t)$;
(2) The compression and expansion process of the piston in the cylinder is an isentropic process.
(3) Ignore the leakage in the cylinder.
(4) Ignore the pressure fluctuations during the suction and the discharge process.

Figure 4 is a schematic diagram of the cylinder in SDVLC. Equations (11) and (12) are the pressure equation for the compression and expansion process in the cylinder. Equation (13) is the dynamic equation of the linear compressor mover. According to Kirchhoff's voltage law, the voltage balance equation on the coil could be obtained by Equation (14) [22]:

$$P(t) = (X_0 + X/X_0 - x(t))^n \cdot P_c \tag{11}$$

$$P(t) = (X_0 - X/X_0 - X)^n \cdot P_d \tag{12}$$

$$m\ddot{x} + c\dot{x} + kx = k_e i \tag{13}$$

$$R_e i + L_e \frac{di}{dt} + K_e \frac{dx}{dt} = u \tag{14}$$

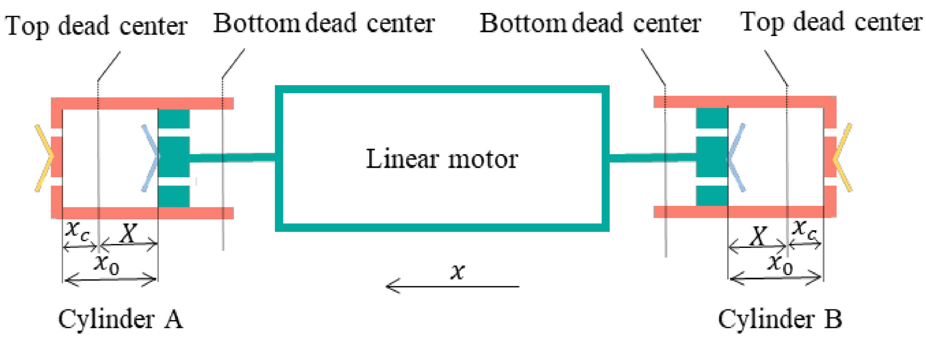


Figure 4. The cylinder of a SDVLC.

The parameters of the linear compressor are shown in Table 2. The linear compressor parameters shown in Table 2, are the parameters and boundary conditions in Equations (11)–(14). The parameters, such as the diameter of the piston, the mass of the mover, stiffness of the flexure spring, thrust coefficient, equivalent inductance and equivalent resistance are the actual parameters of the linear compressor rounded to the nearest value. Where the suction pressure and the discharge pressure are typical operating conditions with a 2.0 pressure ratio in the experiment. The mechanical damping coefficients cannot be measured, they can only be estimated.

Table 2. The parameters of the linear compressor.

Parameter	SVLC	SDVLC
Suction pressure (P_c)	1 MPa	1 MPa
Discharge pressure (P_d)	2 MPa	2 MPa
Diameter of the piston (D)	20 mm	20 mm
Mass of the mover (m)	1 kg	1 kg
Stiffness of the flexure spring (K_s)	200 N/m	200 N/m
Thrust coefficient (K_e)	50 N/A	50 N/A
Equivalent inductance (L_e)	0.2 H	0.2 H
Equivalent resistance (R_e)	1 Ω	1 Ω
Mechanical damping coefficient $\left(c_f\right)$	0.2	0.2

Simultaneous Equations (13) and (14), we could obtain Figures 5 and 6 of the current and velocity.

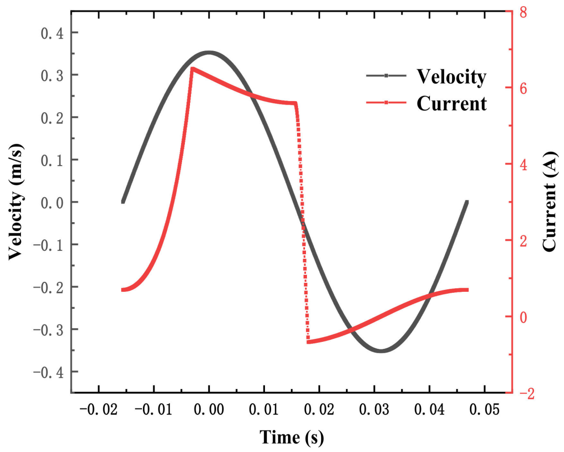


Figure 5. The calculated current and speed curves of the SVLC.

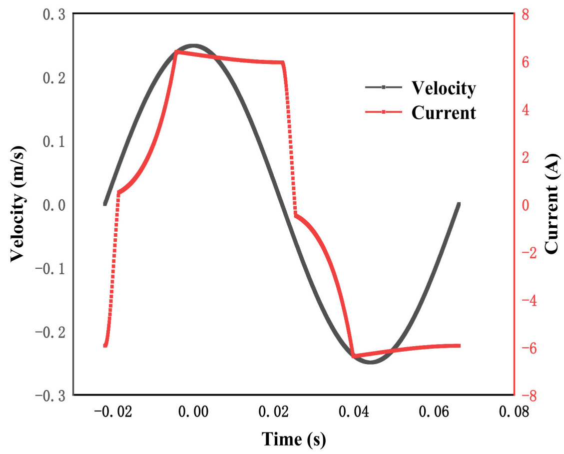


Figure 6. The calculated current and speed curves of the SDVLC.

It could be seen from Figures 5 and 6 that the velocity phase is a standard sinusoidal curve. Consequently, the variance FC can be used to express the degree to which the current deviates from the velocity.

$$FC = \sum_{1}^{N} (i - v)^2 / N \tag{15}$$

where i is the current at each moment, v is the velocity at each moment, and N is the number of data groups.

In particular, it should be noted that the 0 point of the current in Figures 5 and 6 is not at the centre of each figure. Apparently, the velocity and the current are reversed at some moments, as shown in Figures 5 and 6. At this time, the electromagnetic force does negative work, which will reduce the efficiency of the whole linear compressor, the same direction rate TX indicates the degree to which the current goes in the same direction as the velocity.

$$TX = n^+ / N \tag{16}$$

where n^+ is the number of the current and velocity in the same direction in the data $(\mathrm{i} \cdot v > 0)$, N is the total number of data. The specific results are shown in Table 3.

Table 3. Comparison of the variance and same direction rate between SVLC and SDVLC, obtained by the calculation.

	Variances	**Same Direction Rates**
SVLC	50.52	0.715
SDVLC	24.76	0.926

Figures 5 and 6 also describe the current and velocity of the two types of linear compressors, when the pressure ratio is 2.0 and the operation is in the resonance state. It could be found that the current and velocity of the symmetrical dual-piston compressor are more in the same direction. The calculated results describe that the variance of the SVLC is 2.04 times as high as that for the SDVLC in Table 3. The same direction ratio of the SDVLC is 29.51% higher than that of the SVLC. It can be concluded that the current of the SDVLC is more in phase with the velocity than the SVLC. In consequence, from this point of view, the efficiency of the two-piston opposed linear compressor is higher than that of the SVLC.

Figures 7 and 8 indicate the variance and the same direction ratio of the two types of linear compressors with different pressure ratios. It could be found that with the increase of the pressure ratio, the variance increases and the same direction ratio decreases. This demonstrates that the efficiency of the linear compressor decreases as the pressure ratio increases. In addition, it could be concluded from Figures 7 and 8 that the symmetrical dual-piston valve linear compressor has a lower variance and a higher same direction rate at different pressure ratios. Therefore, the efficiency of the SDVLC is higher than the SVLC at different pressure ratios.

The variance and the same direction ratio of the two types of the linear compressors with different frequencies are shown in Figures 9 and 10. Explicitly, with the increase of the frequency, the variance decreases, and the same direction ratio remains unchanged. Consequently, the efficiency of the linear compressor increases slowly as the frequency increases. Similarly, it could be seen from Figures 9 and 10 that the symmetrical dual-piston valve linear compressor has a lower variance and a higher same direction rate at different frequencies. Accordingly, the efficiency of the SDVLC is higher than the SVLC at different frequencies.

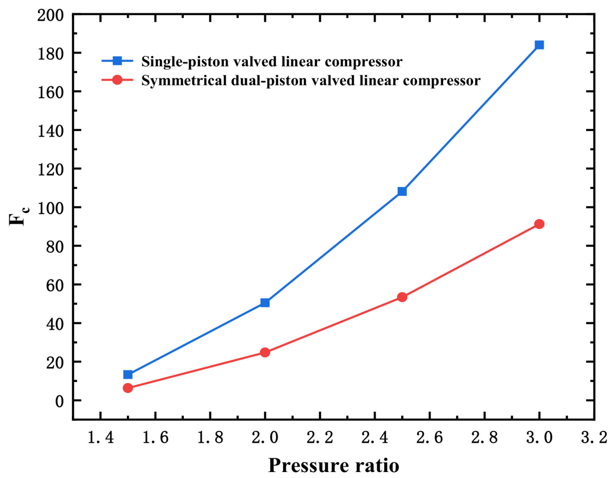


Figure 7. Variances of the two types of linear compressors under different pressure ratios.

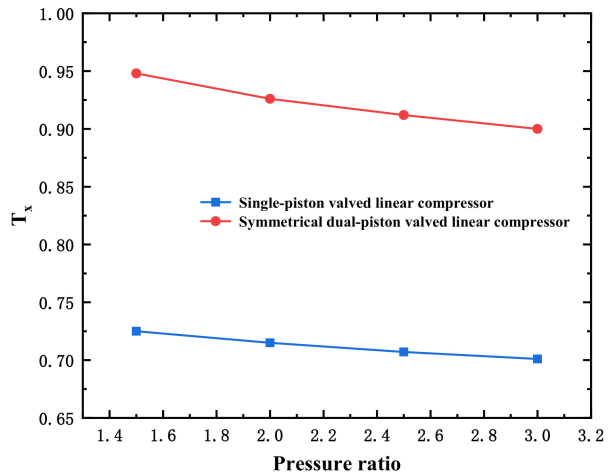


Figure 8. The same direction ratios of the two types of linear compressors under different pressure ratios.

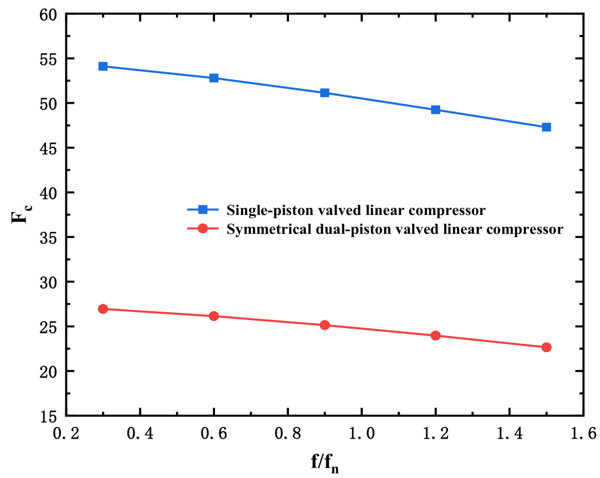


Figure 9. Variances of the two types of linear compressors under a different frequency.

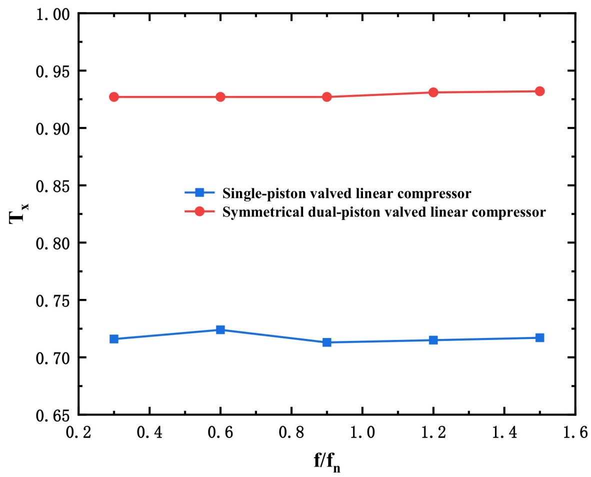


Figure 10. The same direction ratios of the two types of linear compressors under a different frequency.

4. Experimental System Introduction

Figure 11 shows a schematic diagram of the experimental system. Figure 12 shows the photo of the experimental system. The main loop consists of a linear compression, a mass flow meter, a cooler, a low-pressure tank, a throttle valve and a high-pressure tank. Other instruments are thermal sensors, pressure sensors, water coolers, gas cylinders, valves, vacuum pumps, collector, computers, power supplies, power meters, current clamps and oscilloscopes.

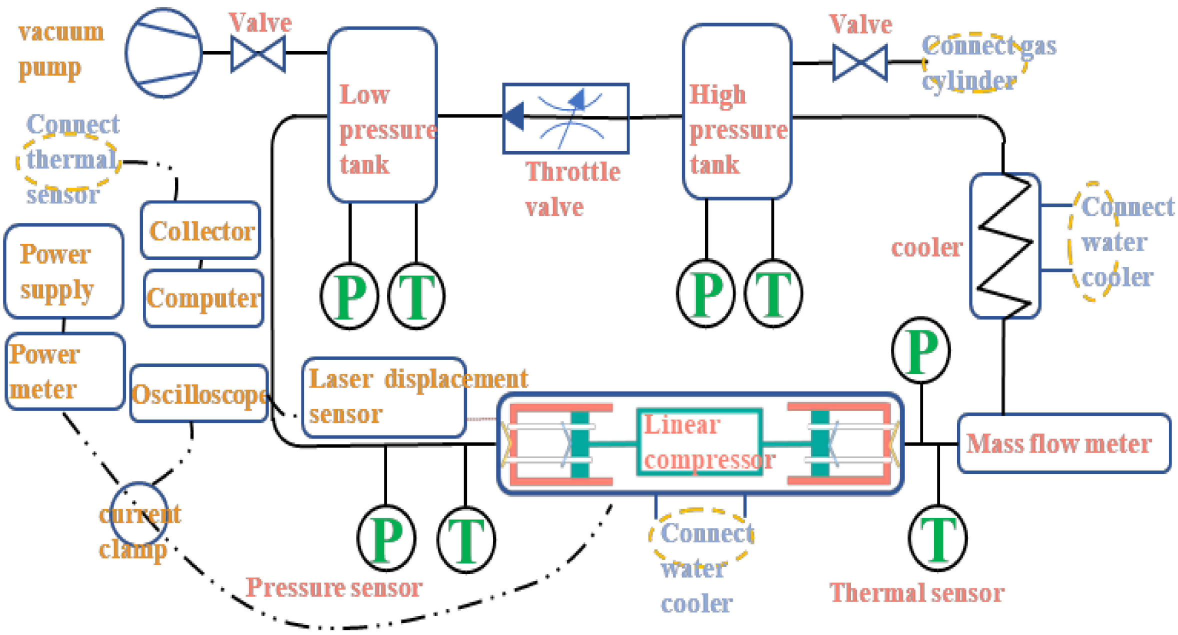


Figure 11. Schematic diagram of the experimental system.

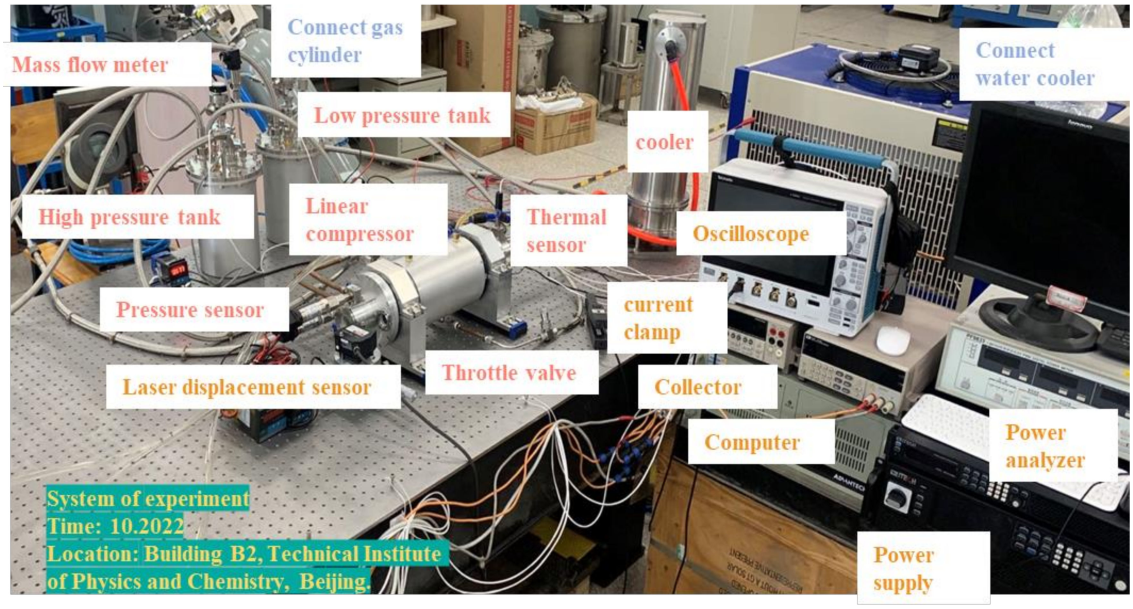


Figure 12. Photo of the experimental system.

The linear compressor converts the low temperature and pressure gas into high temperature and pressure. Then the gas is cooled in a cooler. The throttle valve could control the pressure ratio and mass flow of the loop. Mass flow meters could measure the mass flow of the loop. Thermal sensors and pressure sensors are installed at the linear compressor inlet and outlet, they are used to measure the temperature and pressure of the loop. The stroke of the linear compressor is measured by a laser displacement sensor. The power supply provides the power for the linear compressor and the power meter measures the electrical parameters. The current pliers measure the current waveform. The oscilloscope could display the current waveform and displacement waveform. The key parameters are listed in Table 4.

Table 4. The list of instruments in the experimental system.

Instruments	Model	Quantity	Information
Data acquisition card	NI PCI-6143	1	Sample rate: 250 KS/s; Number of channels: 8;
Data acquisition card	Keithley 7700	1	Sample rate: 1 S/s;
Mass flow meter	Sincerity DMF-1-S3	1	Accuracy: ±0.5%;
Platinum resistor	PT100	4	Accuracy: ±0.1 K;
Static pressure transducer	Hongkong Huibang L61-K	4	Accuracy: ±0.25%;
Laser displacement sensor	Keyence LK-H080	1	Accuracy: ±0.02%; Displacement range: ±18 mm;
Power supply	Itech IT7800	1	Voltage range: 0–600 V; Current range: 0–30 A;
Power meter	Hangzhou Yuanfang PF9833	1	Accuracy: ±1%;
Current pliers	Tektronix A622	1	Maximum current: 100 A; Response frequency: 100 kHz;
Oscilloscope	Tektronix Mdo34	1	Bandwidth: 200 MHz;

5. Experimental Results and Discussion

By adjusting the input voltage and frequency of the power supply, the stroke and operating frequency of the linear compressor can be adjusted. The operating frequency is expressed as a multiple of the intrinsic frequency f_n. The pressure ratio of the system is changed by adjusting the opening of the manual throttle valve. The system operating parameters are shown in Table 5.

Table 5. The system operating parameters.

Parameters	Value
Fill pressure (MPa)	0.7
Stroke (mm)	10
Working fluid	N_2
Operating frequency (f_n)	0.8, 1.0, 1.2, 1.4, 1.6
Pressure ratio	2.0, 2.5, 3.0, 3.5

5.1. Cures of the Current and Velocity

The experimental investigation is carried out using the SVLC and the SDVLC independently, developed in our laboratory. When the pressure ratio is set to 2.0 and the linear compressors operate at the resonant frequency, the experimental results are shown in Figures 13 and 14.

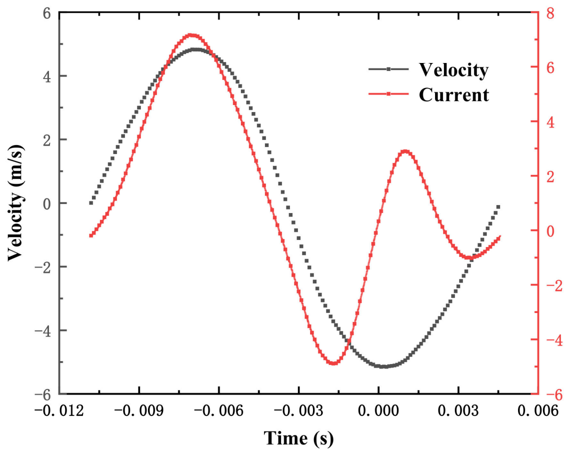


Figure 13. The current and velocity of the SVLC, obtained from the experiment.

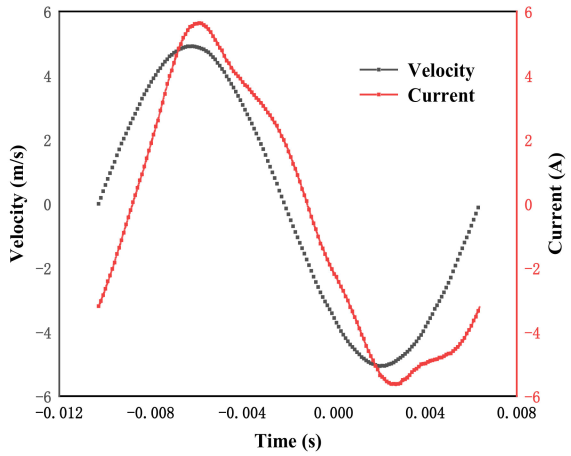


Figure 14. The current and velocity of the SDVLC, obtained from the experiment.

Actually, it could be seen from Figures 13 and 14 that the current and velocity curves of the SVLC deviate significantly in the last 1/2 cycle, while the current and velocity curves of the SDVLC are more consistent. The variance and same direction rate are shown in Table 6.

Table 6. Comparison of the variance and same direction rate between the SVLC and SDVLC obtained by experiment.

Type of Linear Compressor	Variances	Same Direction Rates
SVLC	8.79	0.805
SDVLC	2.88	0.851

The variance of the SVLC is 3.05 times as high as that of the SDVLC. The same direction ratio of the SDVLC is 5.71% higher than that of the SVLC. It could be deduced that the efficiency of the SDVLC is higher than that of the SVLC. The deviation of the current and velocity exhibited by the SVLC is inseparable from its structure. The SVLC's structure causes the load not to be symmetrical during one cycle. When the gas is expanding, the gas force doing the work on the piston causes the current to increase, which is the main reason for the divergence between the current and velocity.

5.2. Isentropic Efficiency

In order to evaluate the efficiency of the linear compressors, the isentropic efficiency η_p is used to evaluate that, and could be obtained by Equation (17) [23]:

$$\eta_p = \frac{k}{k-1} m \cdot R_g \cdot \frac{T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]}{P_{in}} \tag{17}$$

Figures 15 and 16 describe the isentropic efficiency of the SVLC and SDVLC at different pressure ratios and different frequencies. In essence, the isentropic efficiencies of the SDVLC are higher than that of the SVLC at different pressure ratios and different frequencies. The isentropic efficiency decreases when the pressure ratio increases, which is consistent with the calculated results. The isentropic efficiency changes hardly when the frequency increases, which is also consistent with the calculated results. The average isentropic efficiency of the SDVLC is 19.67% higher than that of the single-piston linear compressor at different pressure ratios, while the value is 7% at the different frequencies.

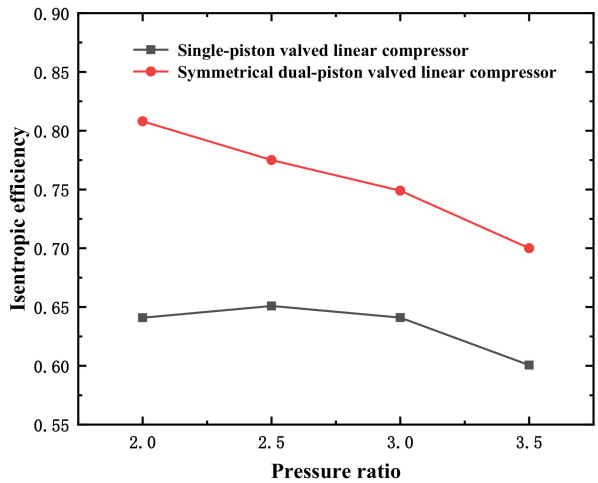


Figure 15. The isentropic efficiencies of the two types of linear compressors at different pressure ratios, obtained from the experiments.

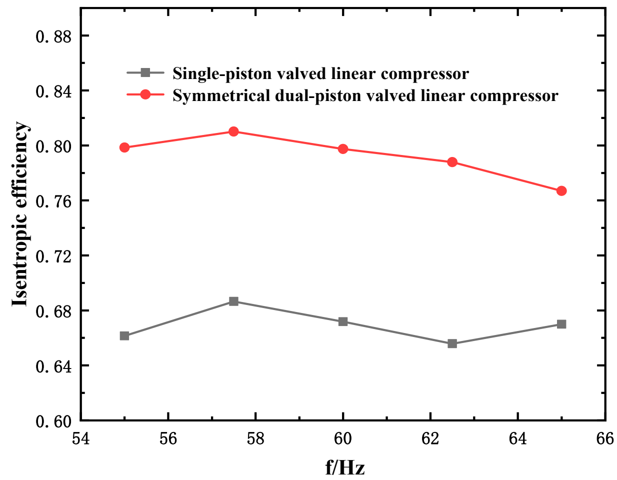


Figure 16. The isentropic efficiencies of the two types of linear compressors at different frequencies, obtained from the experiments.

5.3. Volumetric Efficiency

The clearance volume of the linear compressor has an impact on the volumetric efficiency. Particularly, the load of the SVLC is not symmetrical, the displacement of the piston will further affect the volumetric efficiency. The volumetric efficiency of the linear compressor can be obtained by Equation (18) [24]:

$$\eta_v = \frac{4V}{\pi D^2 S f} \tag{18}$$

where V is the volume flow at the suction port of the linear compressors, D is the piston diameter, S is the piston stroke, and f is the drive frequency.

From Figures 17 and 18, it could be seen that the volumetric efficiencies of the SDVLC are all higher than the SVLC at different pressure ratios and frequencies. As the pressure ratio increases, the volumetric efficiency gradually decreases. The average volumetric efficiency of the SVLC is 79.3% at different pressure ratios. The value of the SDVLC is 83.7%, which is 5.6% higher than the SVLC. As the frequency increases, the volumetric efficiency increases and then decreases hardly. The average volumetric efficiency of the SDVLC is 4.2% higher than that of the SVLC at different frequencies.

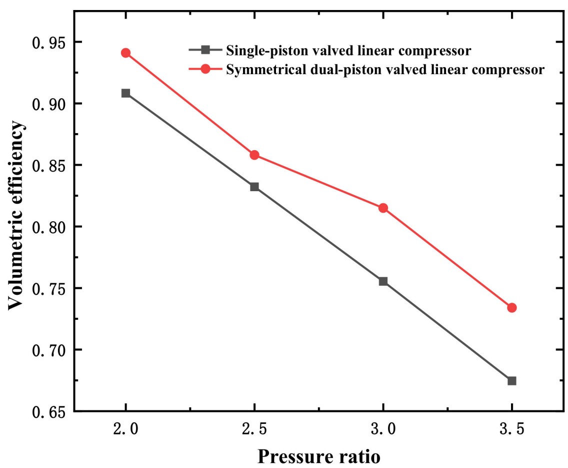


Figure 17. The volumetric efficiencies of the two types of linear compressors at different pressure ratios, obtained from the experiments.

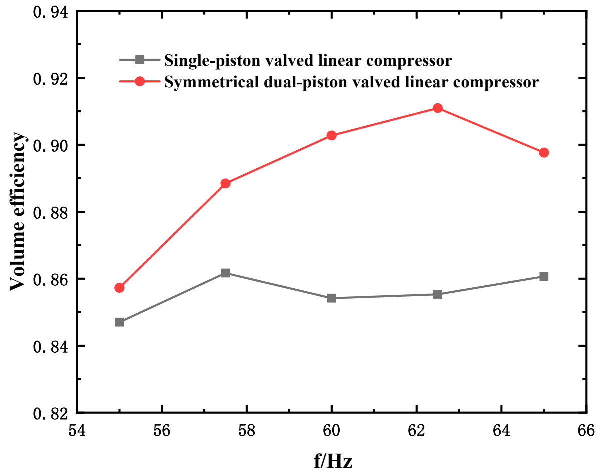


Figure 18. The volumetric efficiencies of the two types of linear compressors at different frequencies, obtained from the experiments.

5.4. Motor Efficiency

The pistons of the linear compressor are powered by moving coils, and the heat generated by the coil copper resistance is a major factor in the motor loss. The motor efficiency of the linear compressor could be obtained by Equation (19) [25]:

$$\eta_m = 1 - \frac{I^2 R_e}{P_{in}} \tag{19}$$

where I is the effective value of the current, R is the resistance of the copper coil, and P_{in} is the input power.

Figures 19 and 20 illustrate the motor efficiency of the two types of linear compressors at different pressure ratios and frequencies. As the pressure ratio increases, the motor efficiency increases and then decreases. The average motor efficiency of the SDVLC is 87.5% at different pressure ratios, and 1.9% higher than the SVLC. The motor efficiency changes in the same way at different frequencies. The average motor efficiency of the SDVLC is 86.5% at different frequencies, and 0.24% higher than the SVLC.

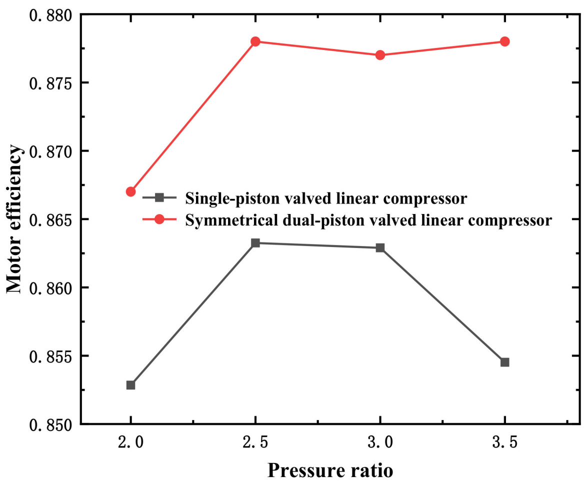


Figure 19. The motor efficiencies of the two types of linear compressors at different pressure ratios, obtained from the experiments.

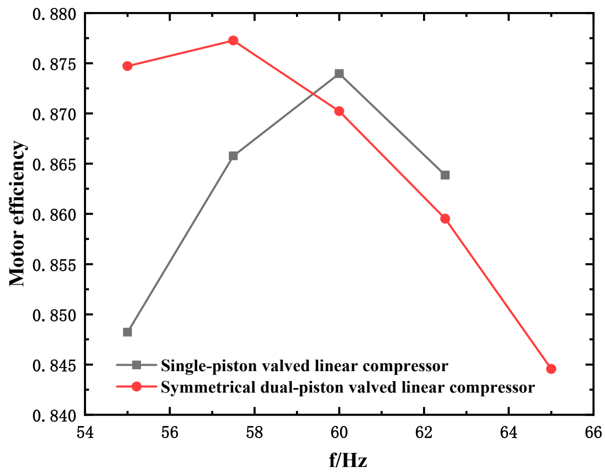


Figure 20. The motor efficiencies of the two types of linear compressors at different frequencies, obtained from the experiments.

6. Conclusions

The paper considers the linear compressor as a single degree of freedom, damped forced vibration system to solve the displacement response. It is deduced that the efficiency is highest when the current is in phase with the velocity. The dynamic equation and the electromagnetic equation of the linear compressor are calculated to obtain the cures of the current and velocity in the time domain. It is found that the current and velocity cures of the SVLC are more deviated after comparison. The variance and the same direction rate are used to evaluate the degree of in-phase between the current and velocity. The SVLC and the SDVLC are tested on the experimental system. The current and velocity cures are obtained respectively. Furthermore, the SVLC and the SDVLC are tested at different pressure ratios and different frequencies. The isentropic efficiency, volumetric efficiency, and motor efficiency of the two types of linear compressors are obtained after the experiments.

1. The variance of the SVLC is 2.04 times that of the SDVLC, but the same direction rate of the SDVLC is 29.51% higher than that of the SVLC. The current and velocity deviation of the SVLC association efficiency decrease. Therefore, it could be concluded that the efficiency of the SDVLC is higher than the SVLC.
2. The experimental results and the calculated results have the same tendency. Under different working conditions, the isentropic efficiency of the SDVLC is higher than that of the SVLC. The average isentropic efficiency, average volumetric efficiency and average motor efficiency of the SDVLC are 19.67%, 5.6% and 1.9% higher than that of the SVLC at different pressure ratios. The values are 7%, 4.2% and 0.24% at different frequencies.
3. The reason for the higher efficiency of the SDVLC is that the current and velocity are more in-phase in the time domain. The in-depth reason is that the load of the SVLC is asymmetric in one cycle, this will cause the current to increase during the half cycle, making the deviation from the velocity. Therefore, the efficiency of the SDVLC is higher than the SVLC.

We conclude that the efficiency is the highest when the current and velocity are in the same phase by solving the dynamic equation. For the linear compressors, the efficiency of the double-piston structure is higher than that of the single-piston structure. We explain the reason for the efficiency difference in terms of the relationship between the current and velocity.

In the future, the efficiency of the single-piston linear compressors will be improved by adjusting the piston offset and reducing the clearance and observing the relationship between the comparative current and speed. It may be possible to increase the efficiency by modulating the current with a device, such as a signal generator that is more in tune with the speed.

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