

Performance Evaluation of Opposed Piston Linear Compressor for Refrigeration Application

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Abstract

In a linear compressor, the volumetric efficiency is a ratio of actual mass flow to the theoretical maximum mass flow. Clearance volume is the space between the top of the piston and the discharge valve. This clearance volume affects the volumetric efficiency of the compressor. At the end of the compression stroke, when the discharge valve closes, a small amount of gas is trapped in the clearance volume. And before suction occurs, this trapped gas needs to be expanded below suction pressure. The expansion of these trapped gases decreases piston stroke, which reduces volumetric efficiency. To enhance volumetric efficiency, the clearance volume should be decreased, thus increasing the mass flow rate and achieving effective cooling. Hence, it is necessary to reduce the clearance volume between the valve and the piston. This paper presents a modified design and modeling of the opposed piston linear compressor and theoretical results. To reduce the clearance volume, modification has been made in the design by making the inlet and discharge port as a model of the previous valve on an inner sleeve and inserting it in the compressor main body.

Keywords

Clearance ratio, clearance volume, opposed piston linear compressor, volumetric efficiency.

Introduction

In any refrigeration and air conditioning system, the compressor plays a significant role by compressing the refrigerant and increasing its pressure to enable it release heat during condensation in the vapor compression refrigeration cycle. The reciprocating compressor uses a slider crank mechanism to convert rotary to linear motion, which increases the rate of wear due to friction and creates noise. To overcome these drawbacks, opposed piston linear compressors are used.

Opposed piston linear compressor (OPLC) is a positive displacement compressor that uses two opposed pistons directly linked to highly efficient linear motors supported by flexural springs to achieve constrained free movement of pistons, which offers easy modulation in the compressor stroke by controlling the supply voltage. This offers comparatively noiseless operation, minimal friction loss and lubrication-free operation of the compressor, as shown in Figure 1.

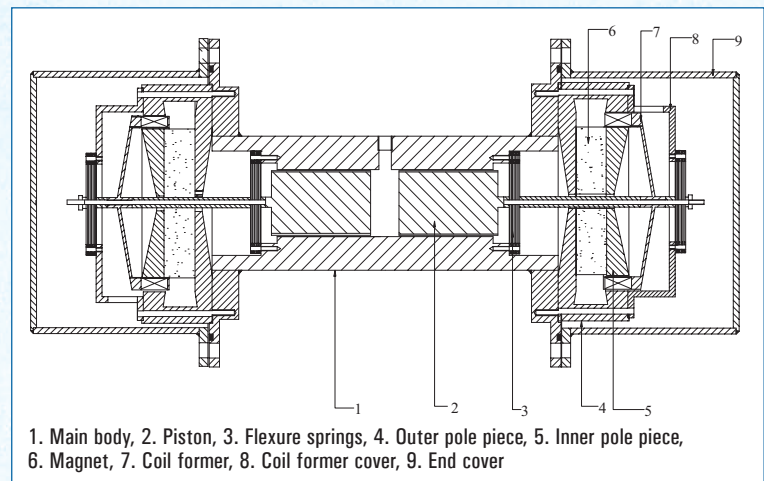


Figure 1: Schematic diagram of opposed piston linear compressor

Clearance Volume

Clearance volume is the gap between the top of the piston and the discharge valve of compressor during its exhaust stroke. In a compressor, when the discharge valve closes at the end of the compression stroke, a small amount of high pressure gas is trapped in the clearance volume. Before the suction stroke, the

This paper was presented at the V National Conference on Refrigeration and Air Conditioning at National Institute of Technology, Surathkal, Karnataka on May 24-26, 2018.

gas trapped in the clearance volume should expand below the suction pressure, but the expansion of this trapped gas in the clearance volume causes a reduction in pressure due to which the volumetric efficiency of the compressor decreases. Therefore, the clearance volume has a significant effect on the volumetric efficiency of the compressor, so it needs to be minimised.

Literature Survey

Hyeong-kook Lee et al. [1] developed a single piston linear compressor free from crank and connecting rod mechanism, whose piston was supported by a helical coil spring driven by a linear motor, with effective cost and energy saving for household refrigerator application. This compressor gives outstanding performance due to its low mechanical loss and minimum clearance volume adjusted with an electronic controller.

Bradshaw et al. [2] discussed that for variable compressor capacity, a compressor with a fixed cylinder size is operated with varying amounts of clearance volume by changing the compressor stroke. As the clearance volume increases, there will be pressure drops across the discharge valve, decreasing the volumetric efficiency. The linear compressor has the ability to recapture the energy during the expansion process imparted by the gas when it operates with variable clearance volume, which makes it suitable for smaller cooling applications.

Wen Wang et al. [3] proposed a compact assembly of rolling piston compressor. The presence of clearance volume is unavoidable; to decrease this clearance volume, they proposed to reduce the mass in the clearance volume, recognized by the overflow method. The result shows improvement in volumetric efficiency with specially designed overflow structure as compared to the conventional compressor.

P. Grolier et al. [4] proposed an analytical method based on both theoretical and empirical approaches for estimating volumetric efficiency considering factors that occur during the working process, which states the performance of a reciprocating compressor. To predict and compare it with experimental results, the clearance volume and temperature of suction gas are required. The variation in capacity and the compression work for different working conditions give a clear idea about compressor performance.

Craig Bradshaw et al. [5] state that volumetric efficiency, frictional and leakage losses and resonant frequency are functions of the stroke-to-diameter ratio for displacement volumes. Smaller values of stroke-to-diameter ratio lower volumetric efficiency, which increases asymptotically with increase in the ratio. As the piston diameter increases, it results in larger clearance volume relative to the displaced volume. Therefore, decrease in the stroke-to-diameter ratio increases clearance volume relative to the piston surface area. Further increase in clearance volume results in a reduction in volumetric efficiency.

Design And Modelling

Design of OPLC

As the proposed OPLC is intended for use in household refrigerators, the first step in design is to select the capacity of the

refrigerator. It has been observed that the demand for higher capacity refrigerators is increasing day by day. So the refrigerator capacity considered here is minimum 360 litres. The typical specifications for high end household refrigerators available in the market are:

Volume = 360 litres; cooling capacity (RE) = 300 watt; current (I) = 1.5 amp; voltage (V) = 230 volts; frequency = 50 Hz. The other parameters are specified in Table 1.

Table 1: Compressor specifications

Item	Value
Input Parameters	
Frequency (Hz)	50
Operating pressure (bar)	5
Refrigerant	R134a
Compressor	
Capacity (cc)	8
Piston	SS304
Piston diameter (mm)	22.5
Total stroke of the piston (mm)	10
Linear Motor Parameters	
Magnet material	Nd-Fe-B
Magnet power (tesla)	1.4
Gap flux density (tesla)	0.85
Coil former	Aluminum
Wire	Copper
Coil wire gauge (SWG)	27
Coil wire diameter (mm)	0.45
Coil wire length (m)	301.4
Motor Force (N)	482
Flexure Spring Parameters	
Flexure material	Beryllium copper
Total stiffness required (N/m)	60,000
Flexure stiffness (N/m)	2000
Flexure thickness (mm)	0.7
Flexure diameter (mm)	69

Capacity Calculation

The CC of the linear compressor is calculated by the following equation:

$$\dot{m} = \rho_s V_s f$$

The mass flow rate for R134a is found from REFPROP software from the standard condition of evaporator and condenser temperatures as specified in Table 2.

Table 2: Operating conditions of OPLC

Particular	Temp (°C)	Pressure (bar)	Density (kg/m ³)	Enthalpy (kJ/kg)
Superheated temperature	T ₁ = 32.2	p ₁ = 1.1484	ρ = 4.7158	h ₁ = 430.46
Subcooled temperature	T ₃ = 35	p ₃ = 11.599	ρ = 1169	h ₄ = h ₃ = 248.98

$$RE = \dot{m} (h_1 - h_4)$$

$$300 = \dot{m} (430.46 - 248.98) 10^3$$

$$\dot{m} = 0.00165 \text{ Kg/sec}$$

$$\dot{m} = \rho_s V_s f$$

$$0.00165 = 4.7158 \times V_s \times 50$$

$$V_s = 7.202 \times 10^{-6} \text{ m}^3$$

$$V_s = 7.202 \text{ cc}$$

$$V_s = 8 \text{ cc}$$

Modeling of OPLC

In CREO 2.0 software, a proper model of linear compressor with proper dimensions is made as shown in Figure 2.

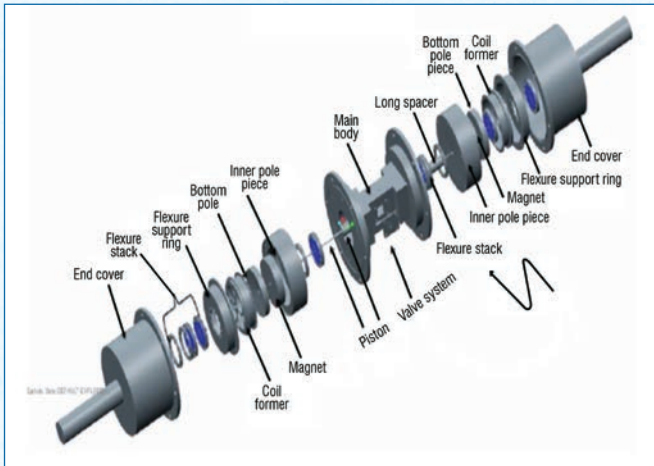


Figure 2: Exploded view of OPLC

Clearance Volume in OPLC

In a single piston linear compressor, the discharge valve is located on the cylinder head, whereas in the case of OPLC both the pistons face each other. Hence, valves are placed on the wall of the cylinder. In OPLC, delivery of the gas is at 90° with respect to the piston axis. The cylinder bore is cylindrical in shape, whereas the valve has a rectangular shape, i.e. a flat surface. So, there is a gap between the piston and the valve known as clearance volume.

Existing Design

In the existing design, the main body has a cylindrical sleeve with a bore for the displacement of piston. Because of the cylindrical sleeve, the valve is mounted on the outer rectangular surface of the main body. So, there is a gap between the cylindrical shape of the bore and the flat surface of suction and discharge valves, which leads to a high clearance volume as shown in Figure 3.

Figure 4 shows the assembly of the main body in the existing design, in which the sleeve is in a circular shape inserted in the main body.

Calculations

Figure 5 shows the dimensions and pictorial view of areas of the existing design for the calculations of clearance volume.

$$A1 = 152.32 \text{ mm}^2$$

$$A2 = 42.39 \text{ mm}^2$$

$$A3 = A1 - A2 = 109.92 \text{ mm}^2$$

$$A4 = 308.95 \text{ mm}^2$$

$$A = A4 - A3 = 199.03 \text{ mm}^2$$

$$\text{Clearance volume} = 199.03 \times 21$$

$$= 4179.67 \text{ mm}^3$$

$$\text{Clearance volume} = 4.17 \text{ cc}$$

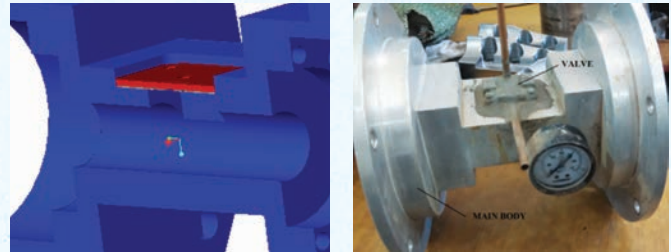


Figure 3: Gap between valve and piston in existing design



Figure 4: Assembly of the main body in existing design

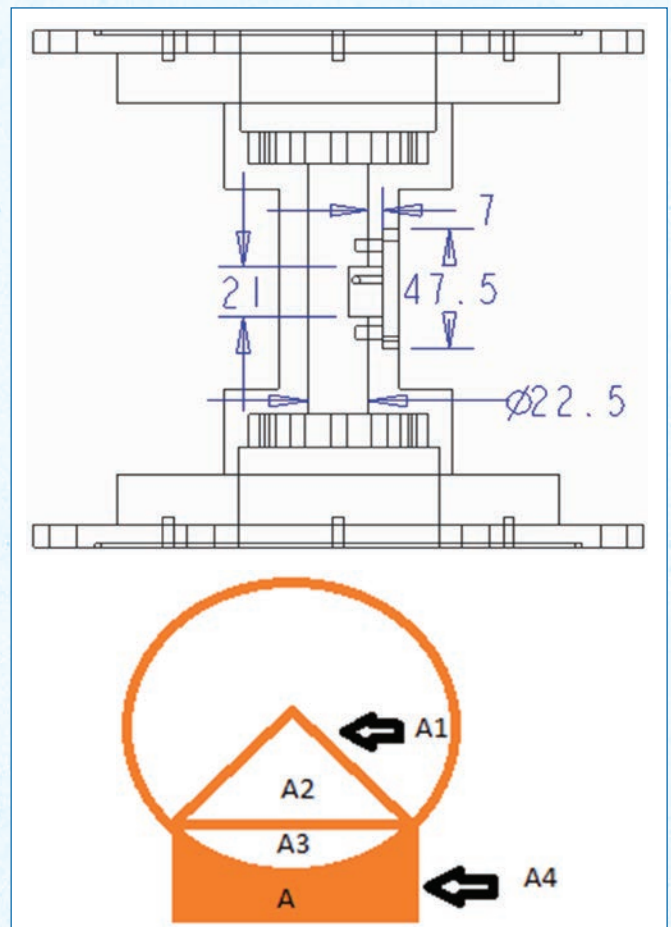


Figure 5: Dimensions of existing design for clearance volume calculation

Modified Design

In the current design, reed valves are generally used in reciprocating compressors. These valves are basically cantilevered beam (flip) type, which move when a differential pressure is applied across them. To avoid back-flow of gas, two separate valves (ports) are used. During suction, the valve opens inside the cylinder, restraining the flow in the outward direction. During discharge, the spring loaded cantilever beam controls the opening and closing of the discharge port. The valve body is created with two separate suction and discharge heads to allow valve motion in only one desired direction; this ensures that suction occurs as shown in Figure 6.

In the new design, to decrease clearance volume, the main body is modified. A sleeve of rectangular shape with a cylindrical bore equal to the piston diameter is press fitted inside the main body, so that the valve can be directly mounted on the sleeve by inserting it through a pocket with a shape as shown in Figure 7, which results in a reduction in the gap between the valve and the piston.

Figure 8 shows the modified sleeve design with a rectangular shape inserted in the main body, on which the valve is mounted. Figure 9 shows a profile made on the sleeve for area calculation leading to the calculation of clearance volume. Table 3 gives different areas of the profile (as shown in Figure 9) divided into various parts.

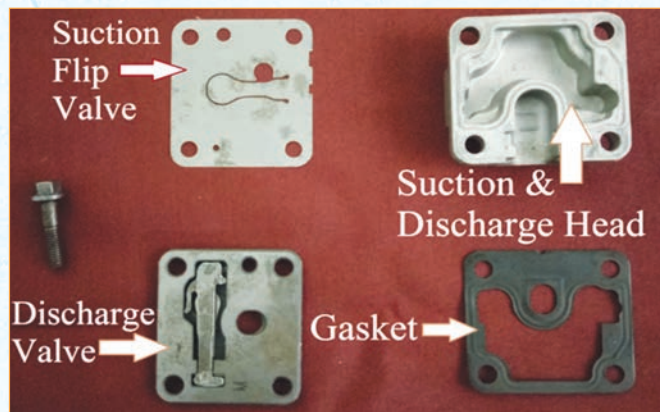


Figure 6: Photos of reed valve assembly used in compressor

= 274.1422 x 2.6

= 712.7697 mm³

Clearance volume = 0.712 cc (approximately 714 cc by CREO software)

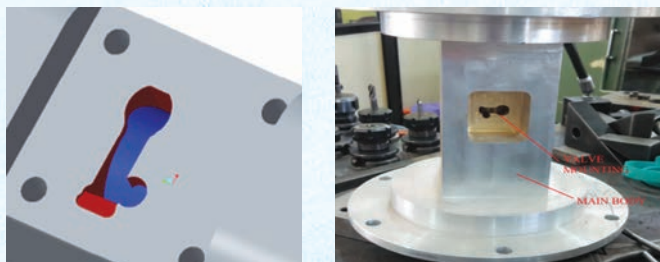


Figure 7: Profile on sleeve for suction valve operation

Results and Discussion

Larger clearance volume reduces the formation of vacuum during the suction stroke, and so a smaller amount of refrigerant is drawn inside for compression; hence, the amount of the refrigerant delivered is reduced proportional to the clearance volume.

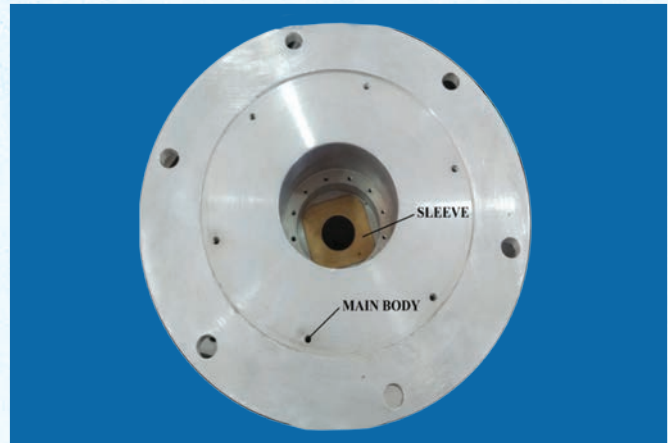


Figure 8: Sleeve design

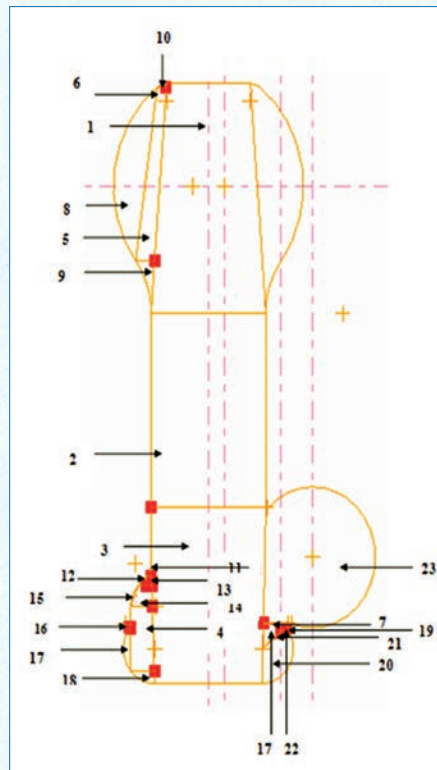


Figure 9: Area calculation of profile on sleeve

Table 3: Areas of modified design

Part	Area (mm ²)
1	45.5928
2	40.975
3	45.1005
4	1.08
5	9.855
6	0.06596
7	3.0193
8	0.0512
9	15.8530
10	1.4292
11	0.03784
12	0.1171
13	0.09635
14	0.7351
15	0.0604
16	1.9970*10 ⁻³
17	0.8163
18	0.42216
19	1.9843*10 ⁻³
20	2.4967
21	0.5715
22	0.1316
23	105.6313
Total area	274.1422

Lesser clearance volume gives higher mass flow rate, which results in increasing the volumetric efficiency, improving the cooling effect. Generally, the clearance volume depends on the manufacturer, but as a thumb rule it is taken between 0.5% to 1% of the cylinder bore.

Volumetric efficiency is calculated as:

$$\eta_v = 1 - C \left\{ \left[\frac{P_2}{P_1} \right]^{1/n} - 1 \right\} \times 100$$

Where,

$$P_1 = 1.1484 \text{ bar}$$

$$P_2 = 11.599 \text{ bar}$$

$$C = \frac{V_c}{V_s}$$

$$V_s = 8 \text{ cc}$$

$$n = 1.3$$

For the old design:

$$V_c = 4.17 \text{ cc}$$

$$\eta_v = -156.62\%$$

For the new design:

$$V_c = 0.714 \text{ cc}$$

$$\eta_v = 56.061\%$$

Table 4: Comparison of C with respect to volumetric efficiency

V_c	V_s	C	P_2/P_1	$1/n$	Vol. Eff.
4.17	8	0.52125	10.1	0.7692	0
4	8	0.5	10.1	0.7692	0
3.5	8	0.4375	10.1	0.7692	0
3	8	0.375	10.1	0.7692	0
2.5	8	0.3125	10.1	0.7692	0
2	8	0.25	10.1	0.7692	0
1.5	8	0.1875	10.1	0.7692	7.69038
1	8	0.125	10.1	0.7692	38.4603
0.714	8	0.08925	10.1	0.7692	56.0606
0.5	8	0.0625	10.1	0.7692	69.2301
0	8	0	10.1	0.7692	100

Table 4 gives different values of volumetric efficiency for different values of clearance volume. Figure 10 shows the graph of clearance volume vs. clearance ratio (C) of the existing design with modified design.

From the graph, it is observed that as the clearance ratio decreases, volumetric efficiency increases. In the existing design, the valve is mounted on the main body, whereas in the modified design it is directly mounted on the sleeve by making a pocket on the surface of the main body, which reduces the gap between the valve and the piston. Also, a pocket is made having the same shape as the suction valve on the sleeve. This further reduces the gap between the valve and the piston, resulting in lower clearance volume. As the clearance is lower, a higher amount of gas is drawn during suction and subsequently delivered during discharge, producing faster cooling.

Conclusion

As the gap between the valve and the piston i.e. clearance volume reduces, the volumetric efficiency improves. Compared with the existing design, reduction in clearance volume from 4.17 cm³ to 0.714 cm³ improves the volumetric efficiency to 56.061%.

The theoretical calculation shows that the volumetric efficiency of opposed piston linear compressor is highly sensitive to changes in the clearance volume, and they should be minimized. Due to manufacturing constraints, clearance volume cannot be made zero. Therefore, it is important to control the clearance volume in any compressor design.

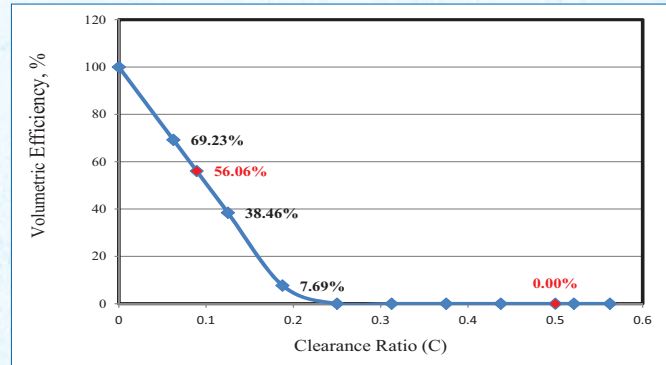


Figure 10: Volumetric efficiency vs. clearance ratio

Nomenclature

\dot{m}	mass flow rate of refrigerant in kg/sec
ρ	Density of refrigerant in kg/m ³
f	Frequency in Hz
V_c	Clearance volume in m ³
V_s	Swept volume in m ³
η_v	Volumetric efficiency
C	Clearance ratio
P_2	Discharge pressure in bar
P_1	Suction Pressure in bar
n	Compression index
A1	Area of sector
A2	Area of triangle
A3	Area of segment
A4	Area of rectangle
A	Area of shaded region

Acronyms

OPLC	Opposed Piston Linear Compressor
CC	Cooling capacity
RE	Refrigerating effect
cc	Cubic centimeter

Acknowledgement

This work was supported by a grant (ISPG_PG_003P) from the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE), New Delhi. The manufacturing of the opposed piston linear compressor and the corresponding experimental setup were carried out at Jayawantrao Sawant College of Engineering.

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