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Design, Development and Testing of Opposed Piston Linear Compressor for Household Refrigerator

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Abstract

Opposed piston linear Compressor is considered to be future of silent, reliable and efficient compression technologies. Unlike reciprocating compressors which are driven by rotary motors and need a crank connecting rod mechanism to convert rotary into linear motion. An opposed piston linear compressor is driven by a linear motor which reduces number of moving parts. This feature makes the compressor more reliable, more efficient and silent operation. The piston (suspended on spring stiffness) in the linear compressor is a free piston i.e. motion of the piston is not constrained hence the performance of the linear compressor is highly dependent on system resonance. Free piston motion offers the unique advantage of ease of modulation i.e. the stroke of the compressor and hence the delivery mass flow rate coming out of the compressor can be easily controlled by changing the supply voltage. In an opposed piston linear compressor, piston performs compression and suction in similar fashion as in the conventional reciprocating compressor. An opposed piston linear compressor exhibits high energy efficiency due to its simple construction and mechanism, its mechanical losses are much less than reciprocating compressor.

Keywords:*Flexure spring, Linear motor, Opposed piston linear compressor, Resonance, Valve system.*

1. Introduction

Compressors play a very important role in the VCRS (**V**apour **C**ompression **R**efrigeration **C**ycle). Compressor is the heart of VCRS as it compresses the refrigerant (R134a), increasing its pressure so as to release heat further in the cycle during condensation. Until now, the reciprocating compressors were used in refrigerators. But they have their drawbacks like high rate of wear, friction, and high pressures by the piston on the cylinder walls and increasing noise level. Reciprocating compressors have high mechanical losses during conversion from rotary to linear motion using crank and connecting rod mechanism. The modern linear compressor technology offers various advantages over a reciprocating compressing machine. This is the most popular among recent compression technologies. It uses a spring-piston arrangement, driven by linear motor. Yingbai XIE et al. [2008] reported that a linear compressor is a free piston-type compressor in which the linear motor drives piston, rather than by a rotary motor coupled to a conversion mechanism as in a conventional reciprocating compressor. Linear motors are simple devices in which axial forces are generated by currents in a magnetic field. Wen WANG et al. [2010] mentioned that the linear motor for linear compressor should satisfy some demands, such as:

A) Enough driving force for piston with compact structure;

B) It is healthier to have lighter piston for better performance. The less weight of piston is responsible for reduction of inertia of the piston and the involved vibration; it gives the advantage to reduce the total weight of the compressor as well.

H.K. Lee et al. [2000] states that the electricity consumption of refrigerator reduced by 50% by replacing the reciprocating compressor in the refrigerator by a linear compressor. The overall noise level of linear compressor also gets reduced by 50% as compared to reciprocating compressor. Ajit S. Gaunekar et al. [1996] reported a typical unit of a flexure suspension system used for linear compressor. Each flexure is in the form of a thin flat circular metal disc having three spiral slots which bear the radial and the axial loads. Each spiral is having sweep angle of 480º. A. Bijanzad et al. [2016] states that to obtain the optimal performance of linear compressor achieving resonance condition is essential. When operating at the resonance frequency, the efficiency of opposed piston linear compressor is increased. Craig R. Bradshaw et al. [2013] states that the resonant frequency of opposed piston linear compressor depends on the mechanical spring i.e. flexure spring and operating gas pressures. To evaluate the resonant frequency, the stiffness of the mechanical spring i.e. flexure spring should be calculated.Haizheng Dang [2015] described the design, manufacturing and assembly method with the special emphases laid on linear motor clearance seal, flexure springs, dual opposed configuration and flexible design. Also mentionedthe material section, geometry design, configuration optimization, manufacturing approaches and optimal assembly to achieve high efficiency, easy productibility, high reliability and long life of the compressor.

1.1 Advantages of opposed piston linear compressor

- Pistons operates in opposite direction with equal amplitude
- Vibration produced by the one piston is cancelled by the other piston.
- Very quiet operation
- No friction loss.
- Good modulation characteristics.

2. Design of Opposed Piston Linear Compressor

2.1 Capacity modulation

As the proposed OPLC is intended to use for household refrigerator, the first step towards design is to select the capacity of refrigerator. It has been observed that the demand of higher capacity refrigerators is increasing day by day. So the refrigerator capacity considered here is minimum 360 lit. The typical specifications for high end household refrigerator available in market is as follows :
Volume = 360 Lit; cooling capacity = 300 Watt; current = 1.5 amp; voltage = 230 volts; frequency = 50 Hz.
The CC of the linear compressor is calculated by following equation.

$$\dot{m} = \rho . V_s . f$$

Where $\dot{m}$ = mass flow rate of refrigerant in Kg/sec.
ρ = density of refrigerant in Kg/m^3
f = frequency in Hz
V_s = swept volume in m^3.
The mass flow rate for R134a is found out from REFPROP software from standard condition of evaporator and condenser temp as follows.

Table 1 ASHRAE-T Conditions

Particular	Temp (°C)	Pressure (bar)	Density (kg/m^3)	Enthalpy (kJ/kg)
Superhe-ated temp	T_1= 32.2	p_1= 1.1484	ρ= 4.7158	h_1= 430.46
Subcool-ed temp	T_3= 35	p_3= 11.599	1169	$h_4 = h_3$ = 248.98

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

$$\dot{m} = \rho . V_s . f$$

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

3. Hardware Development

3.1 Piston with Shaft

It is made of structural steel 304. The diameter of piston is 22.5mm and the length is 46.5mm.It is coated with antifrictional material i.e. Rulon to prevent the leakages of working fluid i.e. R134a from compression space to bounce space. A radial clearance of 15 m is maintained between piston and cylinder.

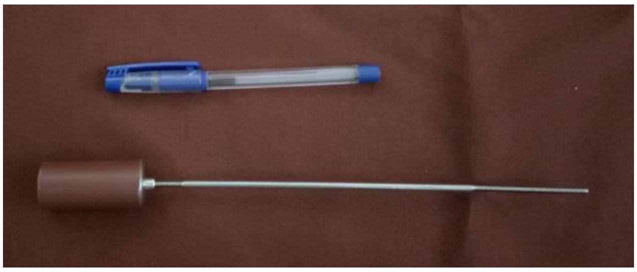

Fig.1 Piston with Shaft

3.2 Flexure Spring

It is made of beryllium copper. Each disc is in the form of a flat metal disc having three spiral slots which bear radial and axial loads. Each spiral sweeps angle of 480 degrees. The function of flexure springs in opposed piston linear compressor is to support the piston and maintain the mean position of the piston.

Fig.2 Flexure Spring

3.3Linear Motor

The static components of the linear motor viz. the magnet, the top pole piece, the bottom pole piece, brass bush. The magnet is in the form of disc shape with 100 mm diameter and 20 mm thickness. It consists of central hole of 10 mm for the shaft to pass through it. The high energy density (1.4 Tesla) Neodium-Iron-Boron magnet is used. The bottom pole piece consists of the same outer diameter as the magnet and central hole identical to that of the magnet. The pole piece sits, on one face of the magnet held firmly in place simply by attractive force of the magnet. The top pole piece, yoke is ring with a C-shaped section and a central hole matching to that of magnet. The brass bush is press fitted in the central hole from the bottom side of the top pole piece to maintain the coaxiality of the top pole piece, bottom pole piece and magnet. The yoke and pole piece are made of pure iron.

Fig.3 Linear Motor

3.4Coil Former

The coil former wall thickness is kept as small as possible to accommodate maximum wire length on it, which would ensure better efficiency of the motor. Aluminium has high strength, low density and is easily machinable and hence was the best choice for coil former. The copper wire of 27 SWG of 0.45 diameter is used for winding of coil former.

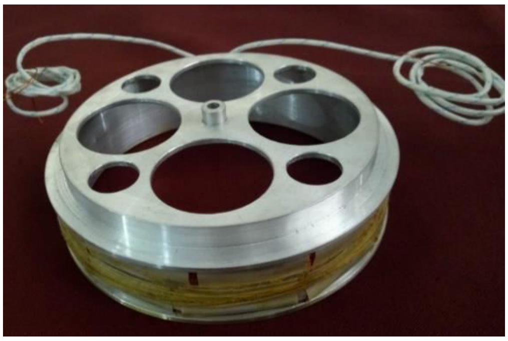

Fig.4 Coil Former

3.5Valve System

The valve system is used for the suction and discharge purpose as same as in the reciprocating compressor. The thin flip plate is suction valve and for discharge valve having a stopper. A gasket is introduced between both plates for preventing the leakages.

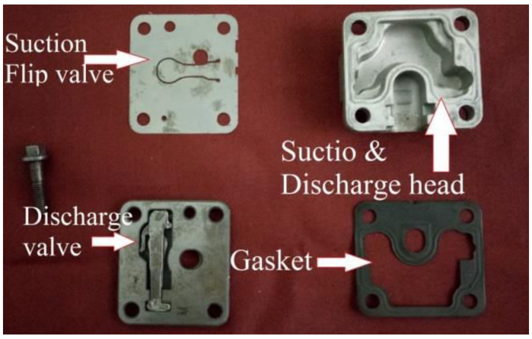

Fig.5 Valve System

3.6 Assembled Compressor

The proper assembly method is followed step by step to assemble the opposed piston linear compressor. Before starting the assembly all the components should cleaned properly with petroleum ether. The assembled opposed piston linear compressor is as shown in the below figure.

Fig.6 Assembled Compressor

3.7 Compressor Specifications

The opposed piston linear compressor is having the above mentioned components. To achieve the desired cooling in the refrigerator as per the objective the specifications of the compressor, input parameters, linear motor parameters and flexure spring parameters were discussed in below table in detail. The below table shows the optimized input and output parameters of opposed piston linear compressor.

Table 2 Optimized input and output parameters of opposed piston linearcompressor

Item	Value
Input Parameters	
Frequency (Hz)	50
Operating Pressure (bar)	5
Working Fluid	R134a
Compressor	
Capacity (cc)	8
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 wire gauge (SWG)	27
Coil wire diameter (mm)	0.45
Coil wire length (m)	301.4
Current through wire (amp)	1.88
Motor Force (N)	482
Flexure spring Parameters	
Flexure material	Beryllium copper
Total stiffness required (N/m)	60000
Flexure stiffness (N/m)	2000
Flexure thickness (mm)	0.7
Flexure diameter (mm)	69

4. Phenomenon of Resonance

Resonance is when operating frequency matches the natural frequency of the body resulting in higher amplitude of vibrations. Achieving resonance in linear compressor results in maximizing the cooling performance of the refrigerator and minimizing the input power requirement and hence increases the COP of the refrigeration system. Natural frequency of opposed piston linear compressor was evaluated experimentally by FFT analysis and it is observed that resonance occurs at 30 number of flexures as 51.246 Hz. As per supply conditions the electric frequency in India is 50 Hz. So at 30 number of flexures natural frequency tunes electric frequency hence resonance occured.

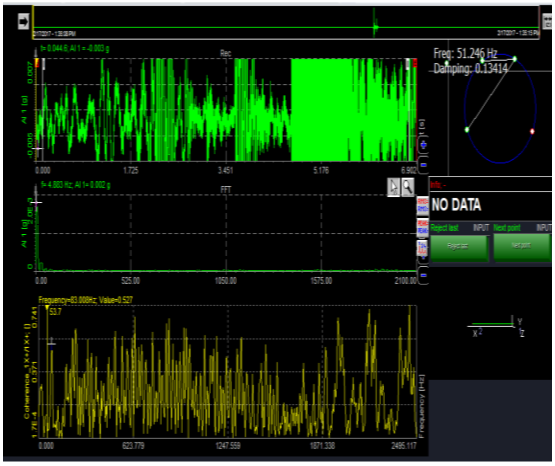

Fig.7 Natural Frequency for 30 flexures by FFT Analysis

Now for the validation of FFT analysis results the natural frequency also evaluated by ANSYS and it was observed that natural frequency tunes with resonance frequency at 30 number of flexures. The natural frequency at 30 flexures is 50.06 Hz.

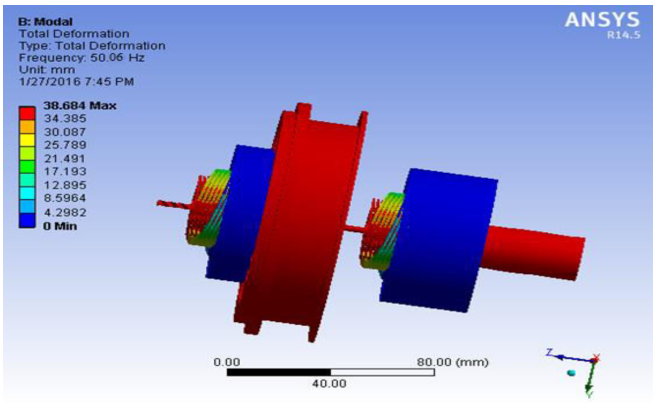

Fig.8 Natural Frequency for 30 flexures by ANSYS

The table below shows the comparison of natural frequencies for different number of flexures by ANSYS and FFT analysis.

Table 3 Comparison of natural frequency

Sr. No.	Number of Flexures	Natural Frequency by ANSYS	Natural Frequency by FFT analysis
1	5	21.828 Hz	22.166 Hz
2	10	30.437 Hz	29.339 Hz
3	15	36.162 Hz	36.630 Hz
4	20	41.164 Hz	41.382 Hz
5	25	45.074 Hz	45.237 Hz
6	30	50.06 Hz	51.246 Hz

The comparison graph of FFT analysis and ANSYS was plotted. The graph represents frequency against number of flexures. The X-axis indicates the number of flexures and the Y-axis represents the frequency.

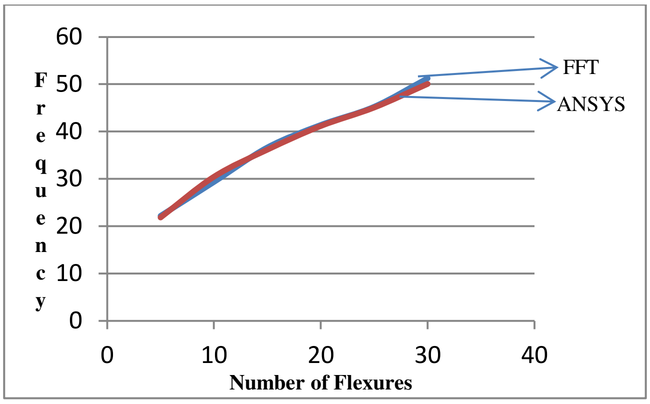

Fig.9 Natural Frequency(Hz) v/s Number of Flexures

5. Experimental Set up

The opposed piston linear compressor is integrated to refrigerator with the help of hose pipes and clips. The hose pipes are connected to copper tubes which are at the suction and discharge of the valve system. The pressure gauges were connected at suction and discharge of compressor for measuring pressure. Multipoint digital temperature indicator is used for measuring the temperature at different points in refrigerator. The Rota meter is coupled with elbow joints at the condenser outlet for measuring mass flow rate. The figure below shows the exact experimental set up and integrated opposed piston linear compressor with refrigerator.

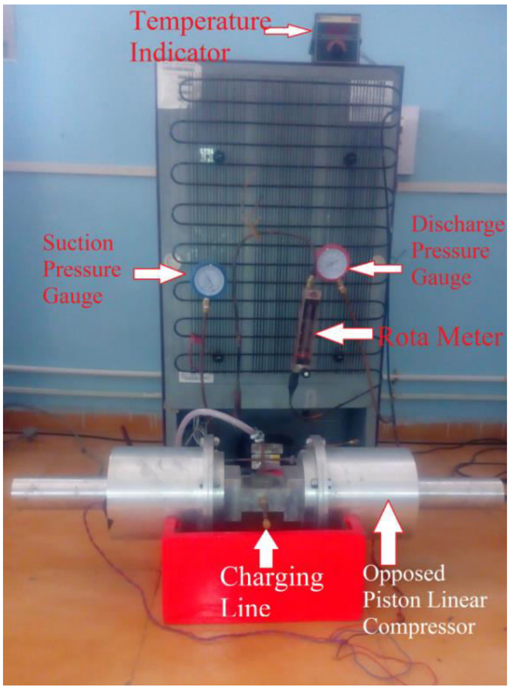

Fig.10 Experimental Set up

6. Results and Discussion

Tests were conducted on developed opposed piston linear compressor integrated with refrigerator. At charge pressure of 5 bar and operating frequency of 50 Hz got the freezer temperature as -20^{0}C. The suction pressure of the compressor was 1.14bar and the discharge pressure was 11bar as seen in the pressure gauges. The condenser temperature is 54.4^{0}C and evaporator temperature is -23.3^{0}C as per ASHRAE-T conditions. At 180 V voltage given by dimmer stat, the current drawn by the system is 2.6A shown by the clamp meter. The mass flow rate of refrigerant (R134a) is 8 Lph measured by Rota meter.

Fig.11 Achieved Freezer Temperature

Fig.12 Temperature v/s Time (Cooling curve)

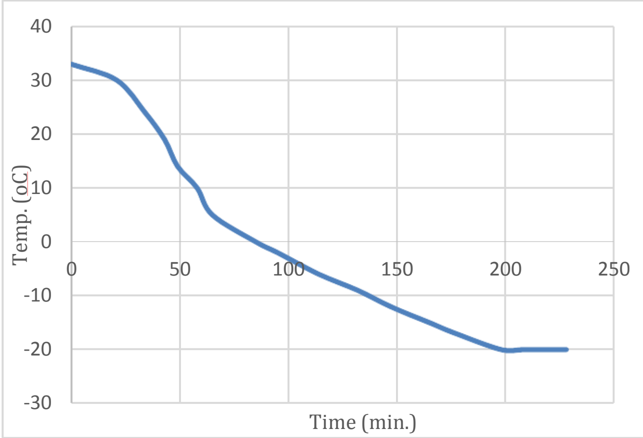

Fig.12 Temperature v/s Time (Cooling curve)

The graph above shows the cooling curve of refrigerator operating with opposed piston linear compressor. To achieve up to 0^o C the time increases rapidly. After that as temperature decreasing below 0^o C the time rises slowly. The freezer temperature achieved -20^o C after 198 minutes.

Conclusion

This paper mentioned the manufacturing of various components of opposed piston linear compressor. The resonance phenomenon was also mentioned studied for tuning the natural frequency of system with electric frequency for better performance of compressor. Resonance occurred at 30 numbers of flexure spring. The discharge pressure observed is 11 bar and the suction pressure is 1.14 bar. The mass flow rate is achieved as 8 LPH which ideally sufficient for the system. From the above graph it has been concluded that the temperature drop up to 0^o C within 85 minutes and after that to achieve temperature below 0^o C time required was 113 minutes i.e. time increases rapidly and cooling effect increases gradually.

Acknowledgement

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