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A Review of Linear Compressors for Refrigeration

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Abstract

Linear compressor has no crank mechanism compared with conventional reciprocating compressor. This allows higher efficiency, oil-free operation, lower cost and smaller size when linear compressors are used for vapour compression refrigeration (VCR) system. Typically, a linear compressor consists of a linear motor (connected to a piston) and suspension springs, operated at resonant frequency. This paper presents a review of linear compressors for refrigeration system. Different designs and modelling of linear compressors for both domestic refrigeration and electronics cooling (miniature VCR system) are discussed. Key characteristics of linear compressor are also described, including motor type, compressor loss, piston sensing and control, piston drift and resonance. The challenges associated with the linear compressors are also discussed to provide a comprehensive review of the technology for research and development in future.

Keywords: linear compressor, household refrigeration, miniature, linear motor, resonance

1. Introduction

A linear compressor does not have a crank mechanism to drive the piston and is driven directly by a linear motor, which has a higher electrical efficiency than a traditional rotary induction motor. Oil-free operation is possible, and this is a significant advantage with respect to the heat transfer performance of the condenser and the evaporator in a refrigeration system and it would allow the use of compact heat exchangers. The absence of oil widens both the choice of refrigerants and their operating temperature range. Eliminating the need for the oil return reduces constraints on pipe sizing and will lead to a reduction in pressure drop losses **[1]**. In a high efficiency linear machine, the piston operates resonantly in order to minimise the drive current and ohmic losses. Resonance is determined by the moving mass and by spring stiffness, which has at least two components, the mechanical springs and the 'gas spring' effect of the compression process: in moving magnet motors the reluctance leads to a magnetic spring effect. The potential for this technology to be scaled to small physical sizes is better than for conventional compressors **[2]**. The refrigeration capacity for system using linear compressors can be modulated by simply changing the excitation voltage.

Linear compressors, with clearance seals and flexure bearings, have been used for many years to power Stirling cycle cryocoolers, and the same technology, with the addition of valves, can be used for vapour compression refrigeration (VCR) systems, with the potential for using ammonia **[3]**. A number of linear compressors have been incorporated into vapour compression refrigeration units with heat exchangers (evaporator and condenser). These units can be domestic refrigeration systems, including fridge/freezer and air conditioner. The other

VCR application using linear compressors is electronics cooling. Oil-free operation of linear compressors enables the use of very compact or micro-channel heat exchangers **[4]**. Miniaturization of linear compressor allows small size VCR system for electronics cooling.

From 1950's onwards, linear compressors have been under development, sometimes in parallel with work on 'free piston' Stirling engines. At an early stage, a linear compressor was investigated by Cadman and Cohen **[5, and 6]** in 1969. It was observed that the free-piston operation of this device produced some peculiar effects such as piston drift, which challenged the modelling efforts and limited the practical application of such devices. Pollak et al. **[7]** investigated the one-dimensional, non-linear dynamics of the piston and electrical systems and confirmed such confounding effects. Since then, a number of experimental works and modelling of linear compressor have been conducted. A few types of linear compressor have been marketed to date. This article reviews the modelling, design and control of different linear compressors for domestic refrigeration and electronics cooling. Key characteristics of linear compressor are addressed including linear motor design, control, efficiency, miniaturization, resonance, piston drift and piston sensing. Challenges are presented and future works are recommended to further extend the linear compressor technology.

2. Comparison with Conventional Compressor

Linear compressors have many advantages over the conventional crank-drive reciprocating compressors. Several investigations have been recently undertaken to compare the performances of linear compressors and the traditional crank-drive compressors. Bradshaw et al. **[9]** utilized the compressor model in Bradshaw et al. **[8]** to compare the energy recovery characteristics of a linear compressor to those of a crank-drive reciprocating compressor and demonstrated that the linear compressor could operate more efficiently over a wider range of dead (clearance) volumes than the crank-drive compressor. Ku et al. **[10]** measured the performances of a moving magnet linear compressor and a brushless direct-current (BLDC) reciprocating compressor, and concluded that the linear compressor had a power consumption reduction of about 10% as compared with the BLDC reciprocating compressor.

Park et al. **[11]** experimentally compared the losses of a linear motor (of Sunpower design) with a rotary induction motor. The linear compressor achieved a 20 - 30% higher efficiency than the reciprocating compressor with a rotary induction motor. Lamantia et al. **[12]** carried out a numerical and experimental analysis of a linear compressor, and their results show that the linear compressor has a higher efficiency than the traditional crank-drive reciprocating compressor due to lower friction losses. Bansal et al. **[13]** reviewed the advantages of linear compressor technologies over traditional crank-drive reciprocating compressors for domestic applications and concluded that linear compressors offer higher efficiency and a more promising alternative to control the refrigeration capacity. Liang et al. **[14]** experimentally compared the performance of a linear compressor with a commercial crank-drive reciprocating compressor. Results show that linear compressor has much higher electrical efficiency (motor efficiency) than crank-drive reciprocating compressor, particularly at low load. However, one of the main advantages of crank-drive compressors is that the position of the piston is well defined by the mechanism, and clearance volumes approaching zero can be achieved, as has been pointed out by Bailey et al. **[4]**. The piston movement in a linear compressor is dependent on the excitation voltage and the piston offset. The piston needs very accurate sensing and control so that it will not collide with the cylinder head when small dead volume is required for higher pressure ratio operation. The piston drift and control will be discussed in Section 6.

Although linear compressor has advantages over traditional compressors stated by both academia and industry, there is lack of comprehensive comparisons between them to quantify the benefits of linear compressor. For example, how oil-free improves the heat transfer particularly with compact heat exchangers is still unknown. Difference of refrigeration performance between linear compressor and equivalent traditional compressors hasn't been measured. Apart from control, another main challenge of linear compressor is the cost. Linear motor requires more rare earth materials. Different manufacturing processes are also required for linear compressor. For example, when manufacturing oil-free linear compressor, a clean room is required to allow radial clearance of 10-20 microns level between piston and cylinder. This is not required for crank-driven compressor as contact seal is used. This is the limitation of large scale production of oil-free linear compressor up to date.

3. Modelling of Linear Compressor

Modelling of linear compressor provides prediction of linear compressor performance and the sensitivity of the VCR system to the design parameters of the compressor. Davies et al. **[15]** built a one-dimension model of a linear compressor shown in Fig. 1. The model includes gas leakage across the radial clearance, force balance on the piston and energy balance for the cylinder. However, the mass and heat transfer in the cylinder is not simulated when the valves open and close. This would lead to non-accurate predictions of mass flow rate and temperatures of suction and discharge. The model is neither capable of predicting high pressure ratio performance as the gas spring will be very nonlinear.

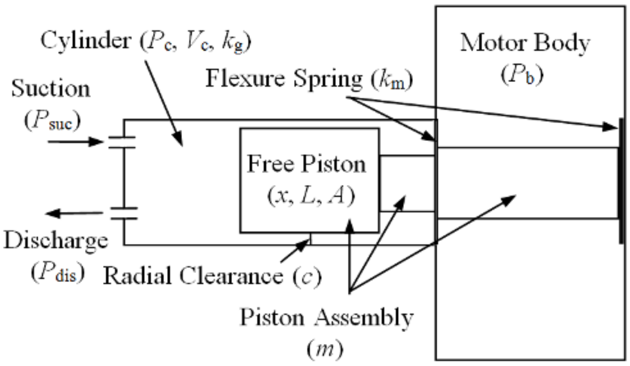


Fig. 1 Schematic of the linear compressor model showing key parameters (adapted from Davies et al. **[15]**)

Bradshaw et al. **[8]** presented a comprehensive model of a miniature-scale linear compressor for electronics cooling. The model consists of a vibration sub-model that is particular to the operation of a linear compressor as well as other sub-models for valve flow, leakage past the piston and heat transfer. The compressor is split into two control volumes (shown in Fig. 2). Bradshaw et al. **[16]** further studied the sensitivity of the compressor model and the resonant frequency. Fig. 3 shows that as the stroke-to-bore ratio increases, the resonant frequency decreases. The overall isentropic efficiency decreases with an increase in stroke-to-diameter ratio as shown in Fig. 4. In addition, the performance improves with a decrease in displacement volume. However, no refrigeration data with validation by measurements were reported. Miniaturisation at higher frequency for electronics cooling is not discussed. This is key aspect when using oil-free linear compressor for miniature VCR system.

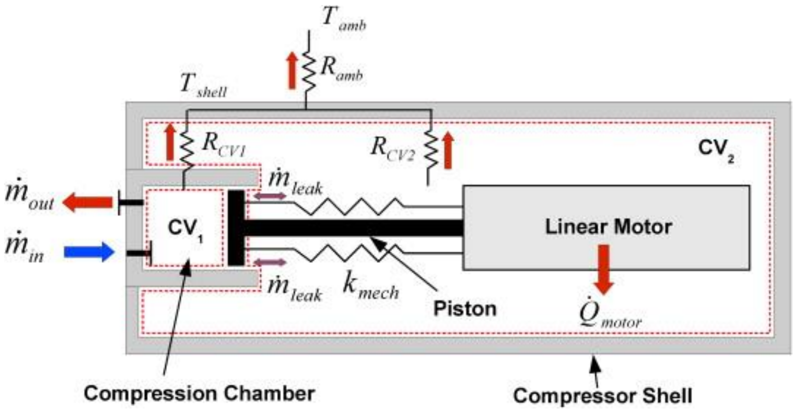


Fig. 2 Representation of the compression process in a linear compressor (Bradshaw et al. **[8]**)

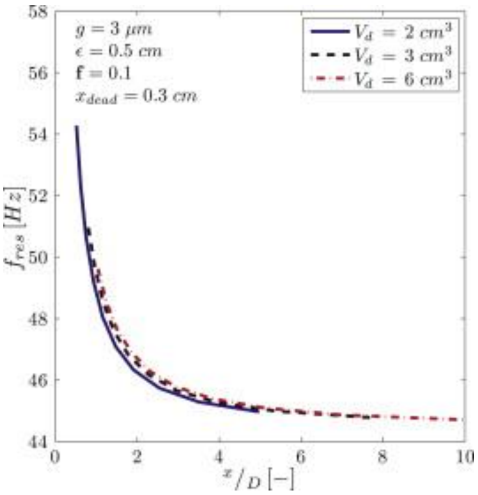


Fig. 3 Compressor piston resonant frequency as a function of the stroke (*x*)-to-diameter (*D*) ratio for three displacement volumes (Bradshaw et al. **[16]**)

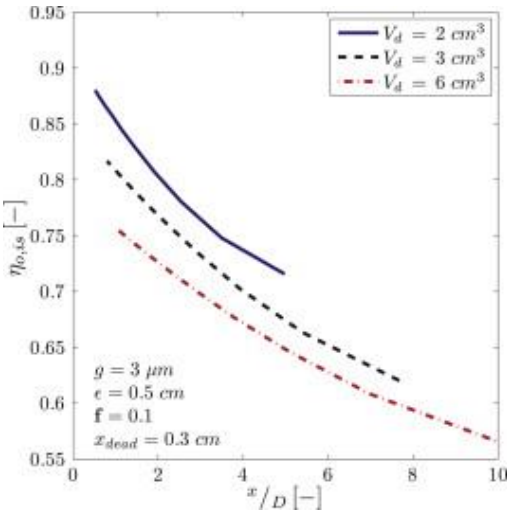


Fig. 4 Overall isentropic efficiency as a function of the stroke-to-diameter ratio for three displacement volumes (Bradshaw et al. **[16]**)

Kim et al. **[17]** simulated the dynamics of a linear compressor for household refrigeration by coupling the electric and mechanical parts (Fig. 5). The non-linear gas spring constant was simulated at higher pressure ratios (over 10). Fig. 6 shows that stroke change of 0.02 mm leads to 2% gas spring constant (0.1 Hz difference of resonant frequency). Though the model is validated by the experimental results, there is no sub-model for gas leakage across the radial clearance seal.

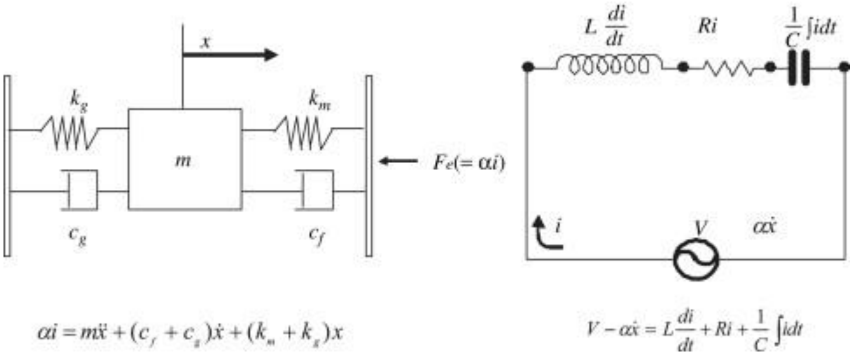


Fig. 5 Simplified model for simulation of the coupled system of the electric part and the mechanical part in the linear compressor, replacing the thermodynamic part with an equivalent parameter in the governing equation (Kim et al. **[17]**)

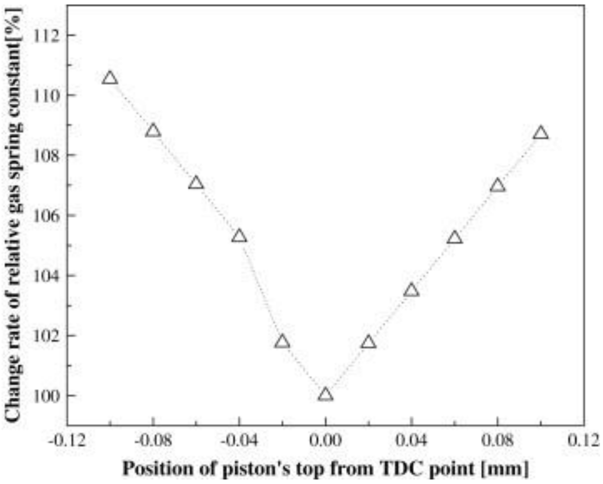


Fig. 6 Simulation result of relative gas spring constant according to the change of piston stroke around top dead centre (TDC) in the linear compressor (Kim et al. **[17]**)

Chen et al. **[18]** presented a model of linear compressor. The simulation results show that the stroke is approximately a linear function of the input voltage. Lamantia et al. **[12]** used MATLAB/Simulink and ADAM to simulate the performance of a linear compressor for household refrigeration. Results show a peak coefficient of performance (COP) at 49 Hz. Liang et al. **[19]** improved the compressor model presented by Davies et al. **[15]** to infer the cylinder pressure. Kim et al. **[20]** developed a numerical model of a linear compressor showing that the cooling capacity was inherently modulated from 55% to 90% over the ambient temperature range without using stroke controller. Park et al. **[21]** performed a thermal analysis of a linear compressor using a heat balance and control volume. Sensitivity to energy efficiency ratio (EER) analysis of each part of the linear compressor was also investigated. Fig. 7 shows that the mixing ratio (flow rate of suction refrigerant which is transferred to the compression chamber directly to the flow rate of total refrigerant) and the shell are the most sensitive to the compressor performance.

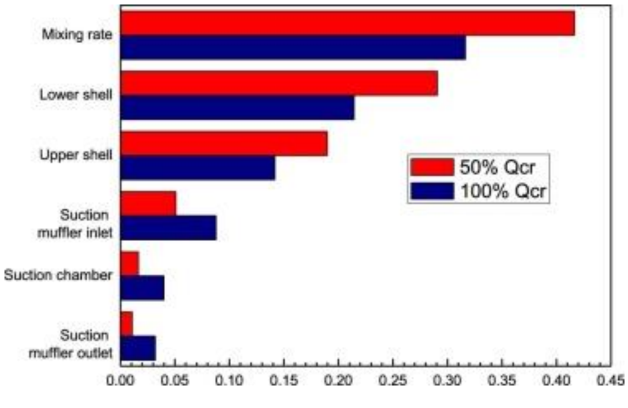


Fig. 7 Sensitivity to energy efficiency ratio (EER) analysis of each part of the linear compressor (Park et al. **[21]**)

Oliveira et al. **[22]** used CFD (computational fluid dynamics) technique to predict the temperature field of an oil-free linear compressor including heat transfer in solid components and along the gas path in the suction system, internal environment and discharge system. In this work, an empirical convective heat transfer coefficient was used to estimate the instantaneous heat exchange between the gas and the cylinder wall. The actual heat transfer between the gas and the cylinder wall is complex due to mass transfer when valves open and close **[23]**. With CFD technique, the instantaneous heat transfer in the cylinder of crank-drive reciprocating compressor has been already investigated **[24 and 25]**. The results should be similar to linear compressor though no such work has been conducted so far.

Comprehensive model of linear compressor should include sub-models of dynamics, mass and heat transfer, thermodynamics, coupling of electric and mechanical systems, motor force, pressure drop across valves, piston drift, gas leakage and very nonlinear gas spring at high pressure ratios. Both 1D and 3D technique are necessary. None of the models mentioned above is capable of simulating the linear compressor including all necessary sub-models. One challenge is the characteristics of linear motor. Most of above studies assumed either a sinusoidal motor force or a constant motor efficiency. The actual motor force depends on the electromagnetic design. Section 6.1 describes the different linear motor designs. Another concern is the very nonlinear gas spring at higher pressure ratios, which determines the resonant frequency. CFD technique is suggested for future work to study the mass and heat transfer in the cylinder considering the gas leakage across the radial clearance seal and valve motions.

4. Linear Compressor for Domestic Refrigeration

One company that has been involved in linear compressor technologies over a long period is Sunpower. They have developed a system using linear gas bearings to support and maintain the alignment of the piston **[26, 27, 28, 29, 30, and 31]**. They have developed a system using linear gas bearings to support and maintain the alignment of the piston. This system has been used in both engines and compressors, and development of these machines is on-going. Unger and Novotny **[32]** introduced a compact moving magnet linear compressor, with a high performance linear motor, as shown in Fig. 8. The Sunpower type moving magnet linear motor, which has been widely adopted, uses a tubular magnet that is cantilevered from the suspension system. The linear motor consisted of inner and outer pole pieces, a coil and a ring of permanent magnets which move axially between the pole pieces. The coil is wound circumferentially and is enclosed by the laminations of the outer pole assembly. High motor efficiency can be maintained, particularly at low load (as shown in Fig. 9). Unger et al. **[30]** used R600a to measure the linear compressor performance when integrated into a refrigerator operating at 50 Hz. The results show that under a freezer condition (-18°C), the COP was 2.5 with a cooling capacity of 40 W, while under a fresh food condition (4°C), the COP was 3.0 at 120 W. One comment that can be made is that the tubular magnet with its radial magnetic field is more difficult to magnetise than a bar magnet, and that the tubular magnet has to be cantilevered from one end, so is more difficult to mount. The radially magnetised tube can be approximated by a number of unidirectional segments but the assembly then becomes more complicated.

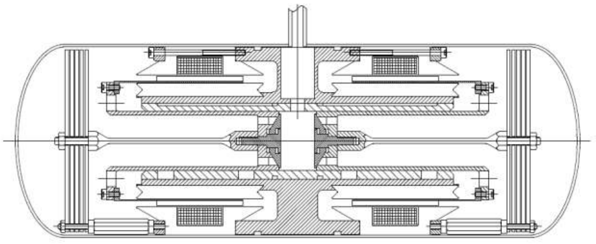


Fig. 8 Sunpower design of linear compressor (Unger and Novotny **[32]**)

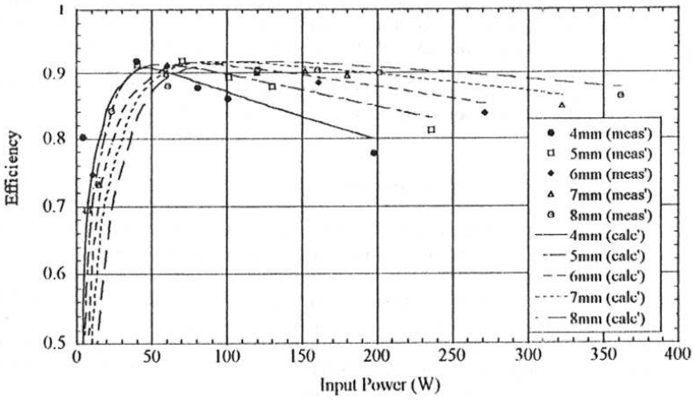


Fig. 9 Motor efficiency of Sunpower linear compressor at different strokes (Redlich et al. **[29]**)

The Korean based LG company have licensed Sunpower's linear technology, and have been marketing linear compressor systems for household refrigerators since 2002 **[33 and 34]**. The configuration of the linear motor is shown in Fig.10. Despite Sunpower's early machines being oil free, the LG compressors designed for R134a and R600a are not oil free and they do not have the gas bearing system. Lee et al. **[35]** presented an iron loss analysis of the linear motor (shown in Fig. 10) using FEA (finite element analysis). Lee et al. **[36]** presented a linear compressor for household refrigerator using a moving magnet linear motor and coil spring. LG stated that their refrigerator using linear compressor (shown in Fig. 11) is much more efficient than those equipped with conventional compressors **[37]**. However, no convincing data has been reported. The main concern of LG linear compressor is much higher cost. Also using very stiff coil spring to dominate the resonance and reduce the piston drift makes the compressor bulky not capable of saving space for refrigeration. Using oil for lubrication in the linear compressor is not attractive as heat exchange will not be enhanced nor the choice of refrigerant. The motor efficiency is not reported to be significantly higher than brushless DC motor (BLDC).

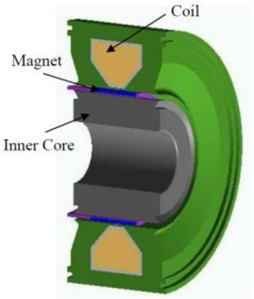


Fig. 10 The linear motor design in the LG linear compressor for household refrigerator (Lee et al. **[35]**)

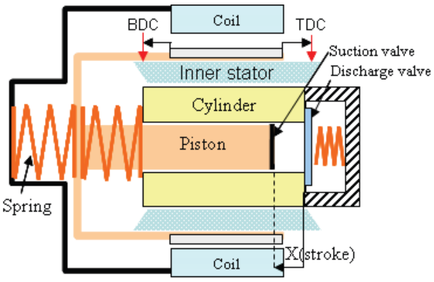
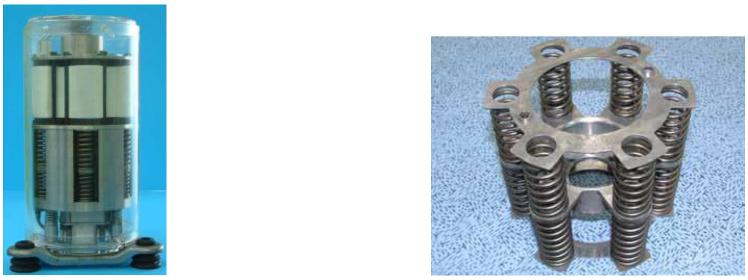


Fig. 11 Schematic of the LG linear compressor configuration for household refrigeration (Yoo et al. **[38]**)

Bradshaw **[2]** purchased a commercial LG refrigerator/freezer (LGC25776SW) to test its linear compressor and measured its performance using R134a. The results showed that a COP of 1.34 was achieved at an evaporator temperature of -5°C and a cooling capacity of 150 W while the isentropic efficiency was 65%. Lee et al. **[39]** adopted a Sunpower design linear compressor for air conditioning as shown in Fig. 12a and concluded that a COP of 3.66 was achieved at the ASHRAE-T condition (evaporator temperature of 7.2°C and condenser temperature of 54.4°C) using R410A. Since the load of air conditioner (1~6 kW cooling capacity) is several times higher than refrigerator, the quantities of the coil springs (see Fig. 12b) and the outline dimension of the linear compressor will be much larger because of the higher gas spring stiffness. Efficiency of the linear compressor with such higher power output may not be very attractive. This may be the reason for no such commercial product so far.



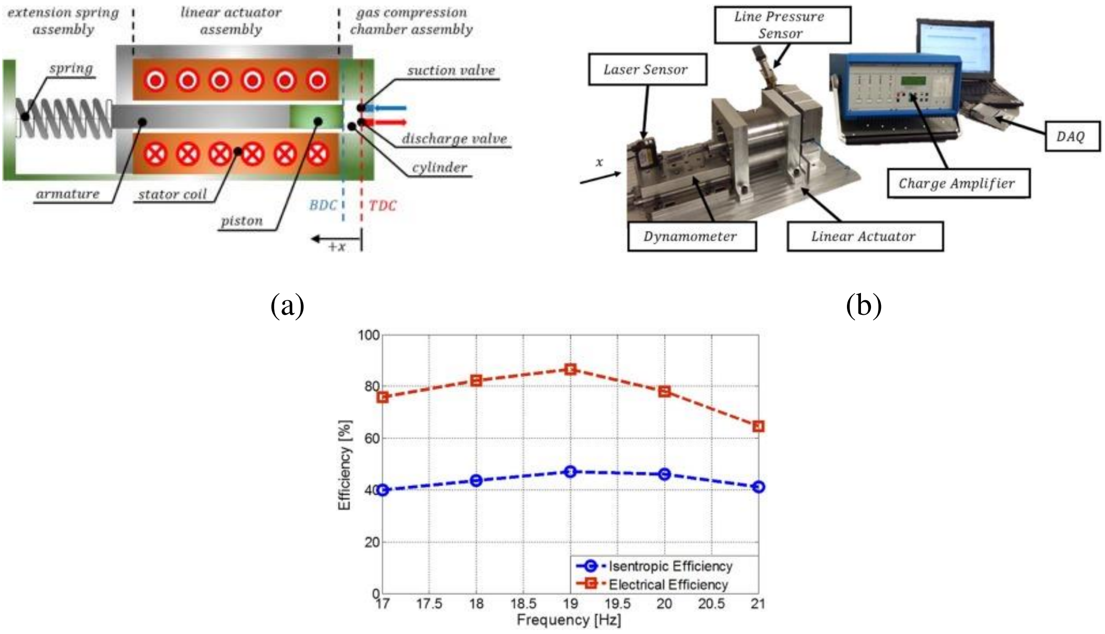
(a) (b)

Fig. 12 Linear compressor (a) and coil spring assembly (b) for air conditioner (Lee et al. **[39]**)

Developments with linear compressors include moving magnet designs in the Clever Fellows (Q drive) **[40]** and in the Infinia design **[41 and 42]**. Q drive design has a complex moving magnet design with multiple coil and magnet assemblies. Infinia have a number of designs that can be either moving magnet or moving iron. They appear to be relatively complicated. More patented design of linear compressors can be found in **[43, 44, 45, 46 and 47]** though there is no reported data of modelling and measurement so far. Note that linear motors of these patented linear compressors are similar to the Sunpower design.

A more recent development by Embraco, is an oil-free linear compressor (Wisemotion Oil-free Technology) designed for domestic refrigeration using R134a and R600a **[48 and 49]**. A patent published in 2008 shows a compressor that has significant similarities with the Sunpower design **[50]**. No published data can be found and no product exists in the market to date.

Bijanzad et al. **[51]** built an oil-free solenoid based linear compressor. The solenoid driven linear actuator is a moving iron type motor, consisting of a stator coil, a stator core and an armature. The piston is directly coupled with the armature and slides inside the cylinder of the gas compression assembly as shown in Fig. 13a. While the coil is excited with the current, the piston moves toward the cylinder. When the coil is de-energized, the energy stored in the springs pulls back the piston to the bottom dead centre. Results show that 85% motor efficiency was achieved at 19 Hz as shown in Fig. 13c. The design appears to be robust but the energy conversion density is much lower. The ratio of shaft force to moving mass is even lower than moving magnet type mentioned above. The benefit of this design is low cost.

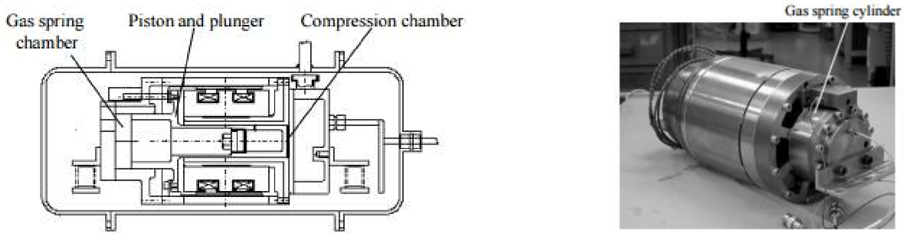


(a) (b)

(c)

Fig. 13 Solenoid based linear compressor for household refrigeration (a); its instrumentation for testing (b); compressor efficiencies against operating frequency (c) (Bijanzad et al. **[51]**)

Hasegawa et al. **[52]** presented a prototype of a linear compressor with a gas spring provided with a self-compensation mechanism (shown in Fig. 14). The motor design is similar to Sunpower design. This design could potentially secure high reliability even in the case of a large stroke and large spring constant, and can be cost effective. The efficiency of the gas spring prototype was 84% of that of a conventional model (mechanical spring prototype). The concern for the design is that when operated at high pressure ratios, the mean piston position will drift. How to control the piston drift is unknown. How gas spring dominates the resonance needs to be further investigated. These could be the reasons for no further reported work based on this design.



(a) (b)

Fig. 14 Schematic of a linear compressor with self-compensated gas spring (a) and its prototype (b) (Hasegawa et al. **[52]**)

For use in household refrigerator, linear compressor ideally should outperform conventional compressors in many aspects. LG design is the only one in the market but higher cost, using oil and coil spring make it not attractive compared with crank-driven compressors. Most of designs so far are similar to Sunpower one which has drawback itself. The moving iron design **[51]** is cost effective but much less efficient. To outperform conventional compressors using BLDC motor, linear compressors should offer motor efficiency of over 90%. This is however very challenging. More novel designs of linear motor are required. Oil-free designs are more favourable. Using refrigerant itself as lubricant could be a solution to reducing cost. Moreover, flexure spring can replace coil spring to reduce the overall size of the linear compressor if piston drift can be solved. For application of higher power output (over 2000 W) such as air conditioner, there is hardly research and development apart from **[39]**. The characteristics of linear compressor are detailed in Section 6.

5. Linear Compressor for Electronics Cooling

5.1 Miniature VCR System

A typical VCR system for electronics cooling is composed of a compressor, a condenser, a throttling device, and a heat sink/evaporator, as shown in Fig. 15. Among the available alternatives, VCR system is one of the only methods which can work in high-temperature ambient, and even result in negative values of thermal resistance. The advantages of refrigeration cooling include maintenance of low junction temperatures while dissipating high heat fluxes, potential increases in microprocessor performance at lower operating temperatures, and increased chip reliability. It is clear that mechanical vapour compression refrigeration is among the most promising of the active cooling technologies to replace conventional air-cooled heat sinks. However, the major concerns involving vapour compression refrigeration systems for electronics cooling are their cost, reliability and most importantly, miniaturization of the system (Bradshaw et al. **[2]**).

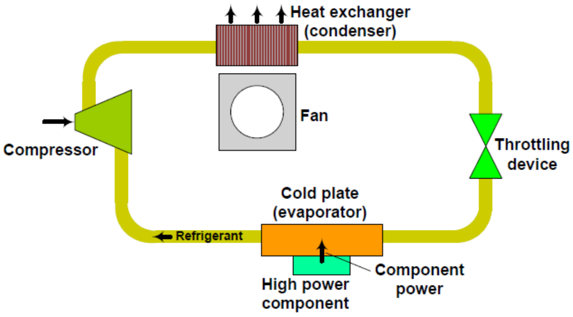


Fig. 15 Schematic representation of a VCR system for electronics cooling (Mongia et al. **[53]**)

A significant number of studies have been carried out in the past ten years or so regarding miniature and small scale refrigeration systems for electronics cooling. Trutassanawin et al. **[54]** summarized commercial refrigeration systems for electronics cooling and conducted numerical and experimental investigations of a miniature VCR system using R134a **[55, 56, and 57]**. Sathe et al. **[58]** experimentally evaluated a miniature rotary compressor for application in electronics cooling. Mongia et al. **[53]** developed an R600a (isobutane) prototype VCR system for portable (notebook) computers using a 12V DC reciprocating compressor and micro-channel heat exchangers. A miniature VCR system was built employing a moving magnet linear compressor by Possamai et al. **[59]**. Other investigations into refrigeration technology have led to the development of system prototypes **[60, 61, 62, 63, 64, 65, 66, 67, 68, and 69]** and system-level models **[70, 71, 72, and 73]**. However, it has been reported by Cremaschi et al. **[74]** that the overall performance and size of these systems are still not at a level that is desired for desktop and portable electronic systems.

The compressor is certainly the most challenging component of the VCR system in terms of its miniaturization. Studies that have dealt with applications in electronics cooling but were not concerned about the actual system miniaturization used small (but not miniaturized) commercially available compressors. Since some commercial compressors are designed for operating at large pressure ratios, their performance is poor at the relatively small pressure ratio often required for electronics cooling, as pointed out by Barbosa et al. **[75]**. Fig. 16 shows a typical VCR cycle for electronics cooling using R134a as the working fluid. The small pressure ratio leads to poor performance for currently available small-scale compressors, which are designed for refrigerator applications with a significantly larger pressure ratio. Small scale or miniature oil-free linear compressors will allow such miniature VCR system incorporating micro-channel heat exchangers for electronics cooling.

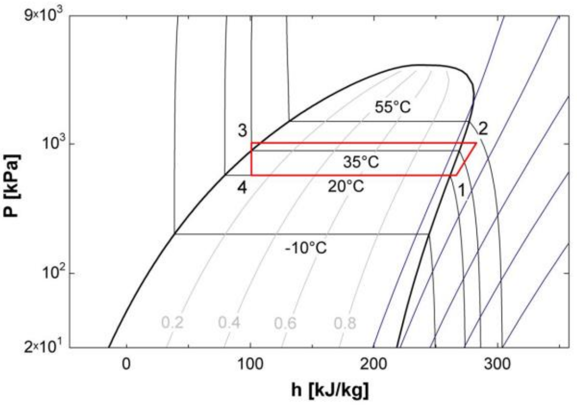


Fig. 16 Pressure enthalpy diagram of typical R134a miniature VCR system for electronics cooling (Bradshaw et al. **[2]**)

5.2 Linear Compressor for Miniature VCR System

Aiming to design small scale refrigeration systems for electronics cooling, a number of linear compressors have been incorporated into vapour compressor refrigeration units with compact heat exchangers (for the evaporator and condenser).

Unger and Novotny **[32]** presented an oil-free linear compressor for CPU cooling (Sunpower design, as shown in Fig. 8). Fig. 17 shows that operated at 95 Hz for a 1250 W cooling capacity using R134a, the coefficient of performance (COP) was 3.6 when the evaporator and condenser temperatures were 20°C and 55°C, respectively. However, this work didn't address solutions and optimization of the entire VCR system, including the evaporator and condenser heat exchangers. The prototype is too large for the miniature VCR system.

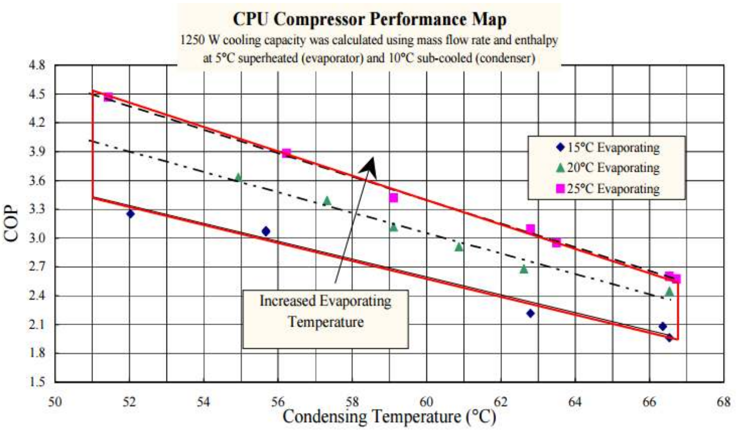
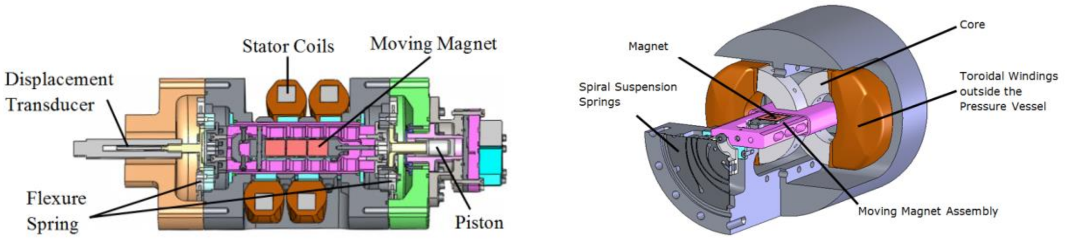


Fig. 17 Performance of an oil-free linear compressor for CPU cooling (Unger and Novotny **[32]**)

The University of Oxford's role in the development of linear machines started in the late 1970's when there was a requirement to cool an instrument on a satellite designed to investigate the Earth's atmosphere. Since then, Oxford-type oil-free linear compressors have been widely used in Stirling cryocooler **[76, 77 and 78]**. Liang et al. **[79]** reviewed three generations of Oxford-type linear compressors (moving coil type). This led to a novel low-cost moving magnet linear compressor, for a project in collaboration with London South Bank University and Newcastle University, to develop a complete VCR system suitable for computer cooling (Davies et al. **[15]**).

Fig. 18a shows the assembled linear compressor, consisting of a moving magnet linear motor, a flexure spring suspension system and the piston-cylinder assembly. There are two identical compressor halves mounted in line, operating in opposite directions to reduce vibrations. Fig. 18b shows the key components of the moving magnet linear compressor. The linear suspension system has two sets of spiral springs to maintain the alignment of the piston within the cylinder. The static assembly has 4 magnetic circuits consisting of coils wound on laminated and slotted cores to form an air gap. The moving assembly (3 rectangular magnets in a line within the air gap) is attached to the piston.



(a) (b)

Fig. 18 Oxford-type oil-free linear compressor for electronics cooling: (a) Moving magnet linear compressor configuration (Liang et al. **[81]**); (b) 100W Oxford moving magnet motor configuration (Liang et al. **[79]**)

Liang et al. **[80]** measured the performance of the oil-free linear compressor using gaseous nitrogen. Liang et al. **[81]** used R134a as refrigerant to measure the performance of the linear compressor. Fig. 19 shows that high electrical efficiency of over 80% is maintained for a wide range of load. The measured evaporator temperature falls between 6°C and 21°C when the linear compressor operates at different strokes (11 mm-13 mm). A COP of 3.2 is achieved at a cooling capacity of 384 W with an evaporator temperature of 20°C (stroke of 12 mm, pressure ratio of 2.5) and a condenser temperature of 54°C as shown in Fig. 20. This is assumed to be a typical CPU cooling condition. However, the Oxford design didn't address the issue of miniaturization as the prototype is rather large and no micro-channel heat exchangers were used. Motor efficiency needs to be further improved by reducing losses.

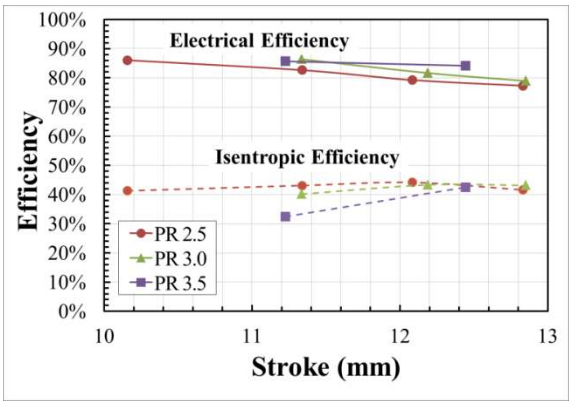


Fig. 19 Electrical efficiency and isentropic efficiency dependency on stroke using R134a for a condenser outlet temperature of 50°C (Liang et al. **[81]**)

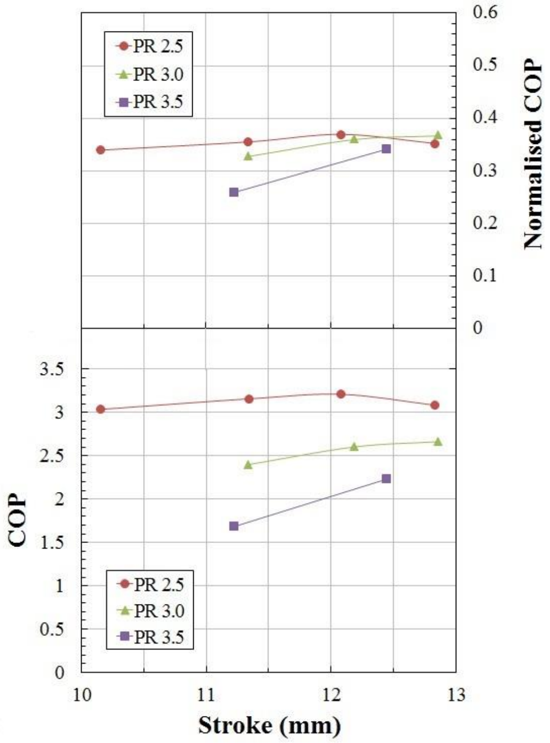


Fig. 20 COP and normalised COP variations with stroke at different pressure ratios with a condenser outlet temperature of 50°C (Liang et al. **[81]**)

Bradshaw **[2]** presented a prototype linear compressor to validate the compressor model (Bradshaw et al. **[8]**). The prototype linear compressor shown in Fig. 21 was driven by a commercial moving magnet type linear motor (H2W Tech) of which the electrical efficiency was assumed to be 41.7%. However, no refrigeration data has been reported since the purpose of the prototype built was merely to validate the model and not to obtain optimized performance. The much less efficient linear motor is not favourable. No high frequency operation is reported.

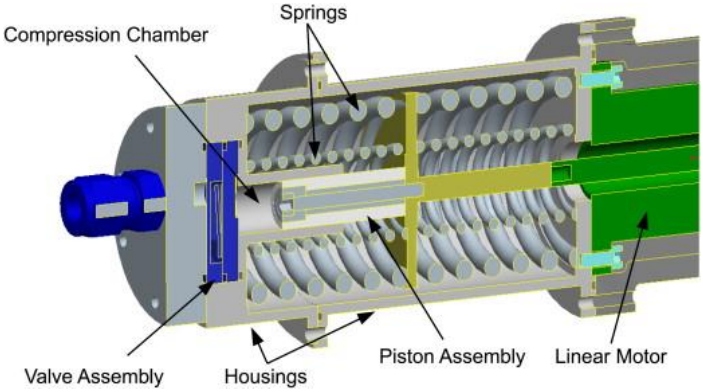


Fig. 21 Section view of the prototype linear compressor (Bradshaw et al. **[8]**)

A moving magnet linear compressor designed by Embraco was utilized by Possamai et al. **[59]** for developing a prototype VCR system using micro-channel heat exchangers for a laptop cooling application. The linear motor efficiency was about 71% (shown in Fig. 22) and the isentropic compression efficiency was about 42%, working with R600a at high operating frequencies. Details of the linear compressor have not been reported but the Embraco moving magnet motor is not efficient with such small size. It can be seen that such miniature VCR system using linear compressor can be used for many innovative applications, where portability is a key issue.

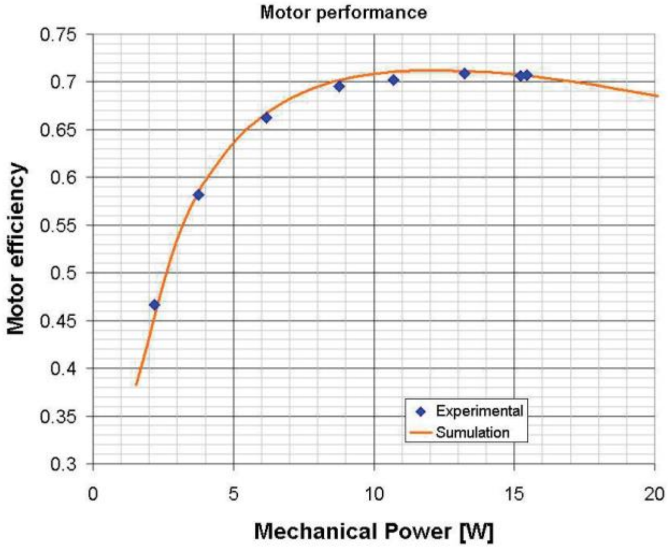
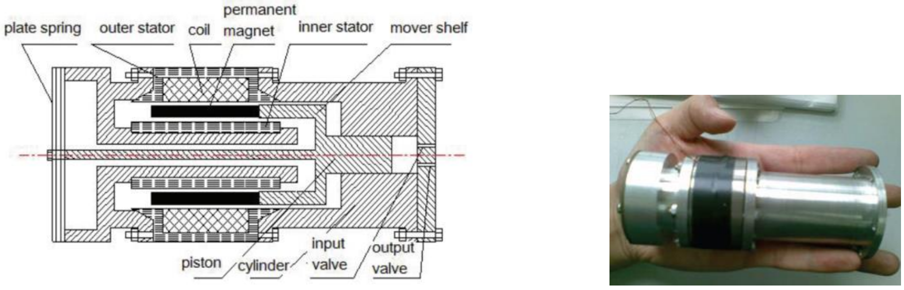


Fig. 22 Efficiency of moving magnet linear motor for laptop cooling (Possamai et al. **[59]**)

Wang and Tai **[82]** presented a prototype miniature linear compressor, based on Sunpower design (shown in Fig. 23). Maximum stroke is 6.5 mm and resonant frequency is 12 Hz. However, the efficiency did not reach the expected values due to significant friction loss and gas leakage across the radial clearance.



(a) (b)

Fig. 23 Schematic diagram (a) and prototype (b) of a miniature linear compressor (Wang and Tai **[82]**)

Alzoubi and Zhang **[83]** presented a compact VCR system using linear compressor. The prototype unit is able to achieve a high coefficient of performance (COP) of 4.5. The VCR system shown in Fig. 24 consisted of a high performance 300W linear compressor with variable capacity control, expansion valve, air-cooled condenser, and two micro-channel plate heat exchangers acting as evaporator and recuperator. No detail of the linear compressor was reported.

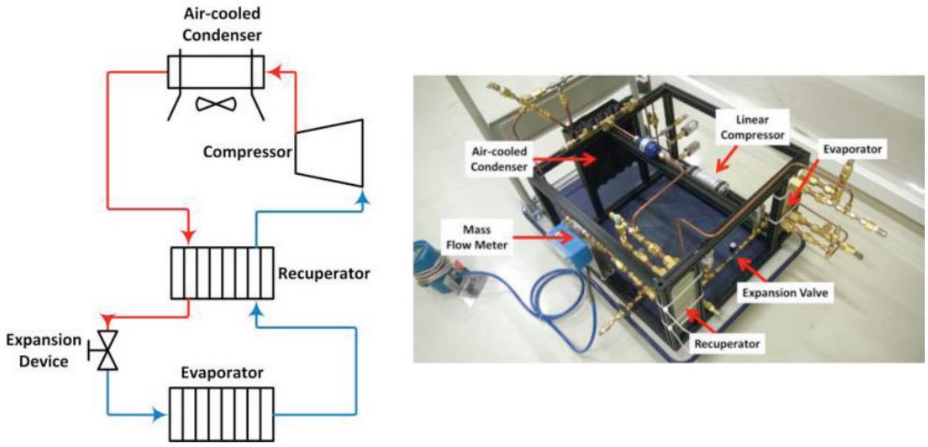


Fig. 24 Schematic and prototype of compact VCR system (Alzoubi and Zhang **[83]**)

Mancin et al. **[84]** reported a mini VCR for electronic thermal management in avionic applications. The water cooled miniature scale refrigeration system (shown in Fig. 25) used R134a as working fluid and adopted a new concept oil-free linear compressor prototype. In the range of pressure ratios from 1.54 to 3.75, the cooling capacity of the VCR system varied from 37 W to 374 W, while the coefficient of performance (COP) ranged between 1.04 and 5.80. No detail of the linear compressor was reported apart from the supplier Embraco, who designed the moving magnet linear compressor for the portable miniature VCR system presented by Possamai et al. **[59]**. It is very interesting to see that Embraco is involved in both miniature linear compressors for electronics cooling and larger version for household refrigeration though there is hardly any published data regarding the compressor itself.

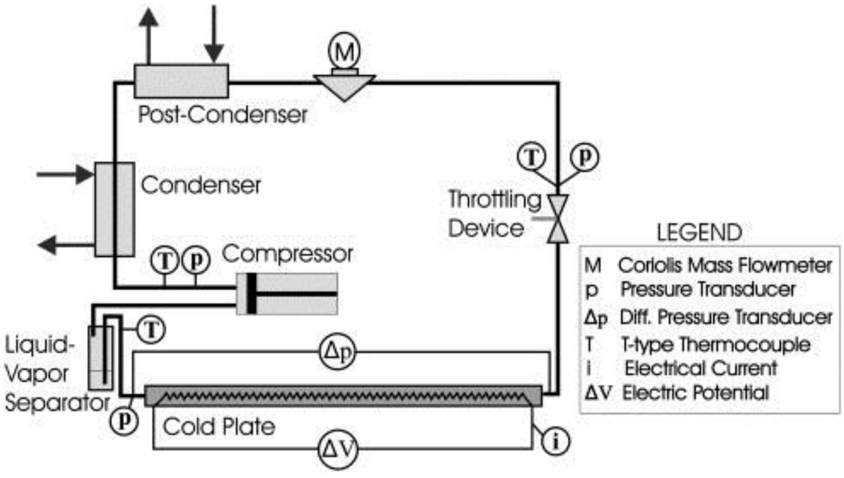


Fig. 25 Schematic of the mini-VCR instrumentation (Mancin et al. **[84]**)

For use in miniature VCR system for electronics cooling, linear compressor needs to be oil-free and miniaturized at higher operating frequency. Designs of Sunpower [32], Oxford [79, 81], and Bradshaw [2, 8] didn’t reach miniature level. It can be seen that Sunpower and

Oxford designs did offer high motor efficiency (over 80%). The only miniaturized linear compressor came from Embraco but apart from the low motor efficiency, there is no published data. It is also unknown why the Embraco design has such low motor efficiency with low power output. More studies on high frequency miniature linear compressor with higher efficiency are necessary in near future. This would eventually allow the use of micro-channel heat exchangers for cooling portable electronic devices.

6. Linear Compressor Characteristics

Key characteristics of linear compressor are addressed to give insight into the design, control and operation of linear compressors for refrigeration. The summary is based on the modelling and measurements described above.

6.1 Linear Motor Type

Linear motor is the key component of a linear compressor. The requirements for an ideal linear motor are as follows (Bailey et al. **[1]**):

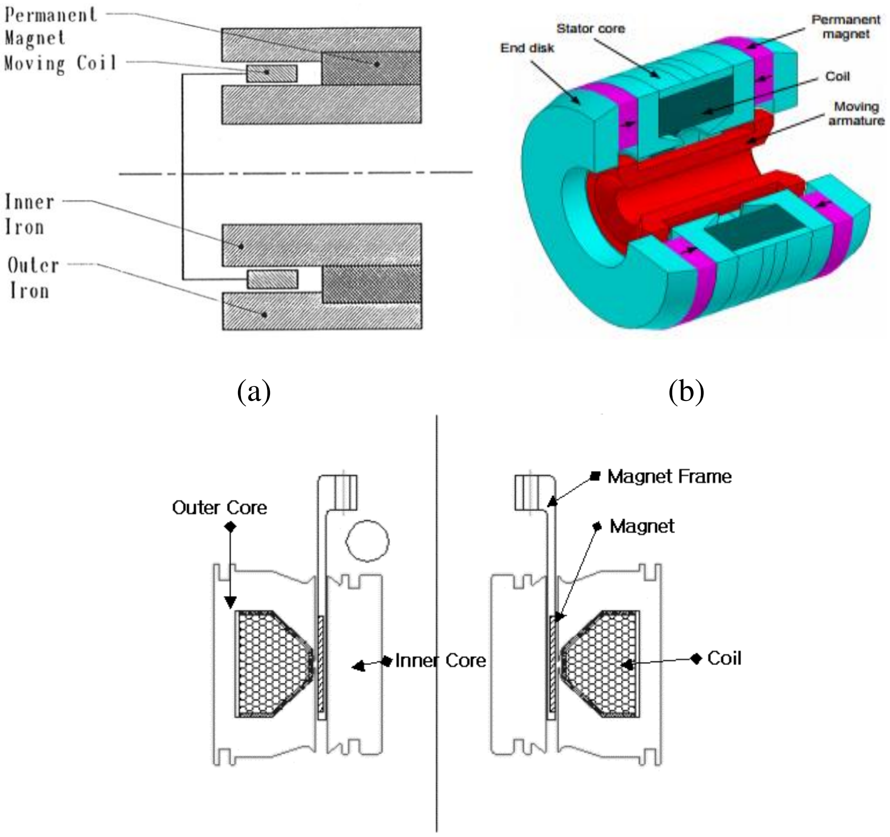
(1) Low cost: small amount of magnet material; low cost components that exploit conventional production methods.
(2) Capable of high efficiency.
(3) Low moving mass.
(4) Simple, robust construction compatible with a spiral spring suspension system.
(5) Static coils that are external to the pressure vessel.
(6) Small envelope.
(7) No magnetic forces acting when coil current is zero (this helps alignment during assembly).

There are mainly three types of linear motors: moving coil, moving iron and moving magnet. Wang et al. **[85]** summarized the three types of linear motors as shown in Fig. 26.

A typical moving coil linear motor (shown in Fig. 26a) is similar to those widely used in loudspeakers. A static magnetic circuit produces a high radial magnetic field in an annular air gap. The drive coil is positioned in the air gap and when it is energised with a current it develops an axial force. The application of an oscillating current to the motor causes the piston to reciprocate, but without any side forces. The moving coil motors are easy to design and to control the stroke. However they require large amount of permanent magnet to achieve high efficiency. And big size of the moving coil motor due to its low power density makes it difficult to be adopted for the compressors of household refrigerators. Another aspect of a moving coil motor that results in complexity and added cost is the requirement for various components to transmit electrical current from the external power source to the moving drive coil. Moving coil motor has been widely used in cryocoolers for many years **[87, 88, 89 and 90]**.

Moving iron motors (shown in Fig. 26b) have stationary magnets and stator coils in which flux linkage reversal occurs as the toothed armature reciprocates backwards and forwards. They are robust but the energy conversion density is much lower compared to other two types of linear motors. Moreover, the shaft force per moving mass is even lower, making it difficult to facilitate the resonant operation at the supply frequency with minimum spring stiffness (Wang et al. **[85]**). Moving iron motors are preferred when the cost is the main criterion (Zhang et al. **[91]**). Bijanzad et al. **[51]** presented a prototype of solenoid based moving iron motor (see Fig. 12) for household refrigeration, which achieved a peak electrical efficiency of 87%.

The recent development of high-energy permanent magnets-such as NdFeB - helps design moving magnet types of linear motors efficient and compact. For the Sunpower moving magnet design shown in Fig. 26c, the stator is divided into outer and inner one by the moving magnets embedded in a rigid frame. The stators are laminated in the radial direction to reduce eddy current loss. Because of high magnetic flux density of NdFeB, the moving magnet motors can generate enough force with small amount of magnets. Therefore, the moving assembly (magnets and piston) is much lighter compared to that of other types of motors. Small moving mass means ease to design the springs for the resonance operation of the linear compressor.



(a) (b)

(c)

Fig. 26 Schematic of three types of linear motors: (a) Moving coil (Redlich et al. **[29]**); (b) Moving iron (Ibrahim et al. **[86]**); (c) Moving magnet (Lee et al. **[35]**)

For low cost, the choice is really between moving magnet and moving iron designs. The moving magnet type is major trend for the high-power rate of linear motors. Zhang et al. **[92]** concluded that regardless of the high cost of permanent magnets, the moving magnet type is major trend for the linear compressor of household refrigerator. Apart from Bijanzad et al. **[51]**, linear compressors described in Section 2 and 3 use moving magnet linear motors. More studies on moving magnet linear motor can be found in **[93, 94, and 95]**.

Whilst it is desirable that the motor should be compact, this is not considered to be a driving requirement for many applications. It also has to be noted that the spring suspension system occupies a significant amount of space, so that reducing the motor size below certain limits is not necessarily very beneficial. The main challenge is how to reduce the losses such as copper loss, eddy current loss in order to achieve motor efficiency of over 90%. This will allow linear motor to compete with BLDC motor which has efficiency of 90% already. Moving magnet type will dominate as the cost of high-energy permanent magnets will go down with consistently more supply from nations such as China.

6.2 Capacity Modulation

The mass flow rate for refrigeration system using a linear compressor is simply controlled by amplitude or stroke modulation, as shown in Fig. 27. This means that there is no need for stop-start operation in which temperature gradients have to be re-established as pointed out by Tassou et al. **[96]**.

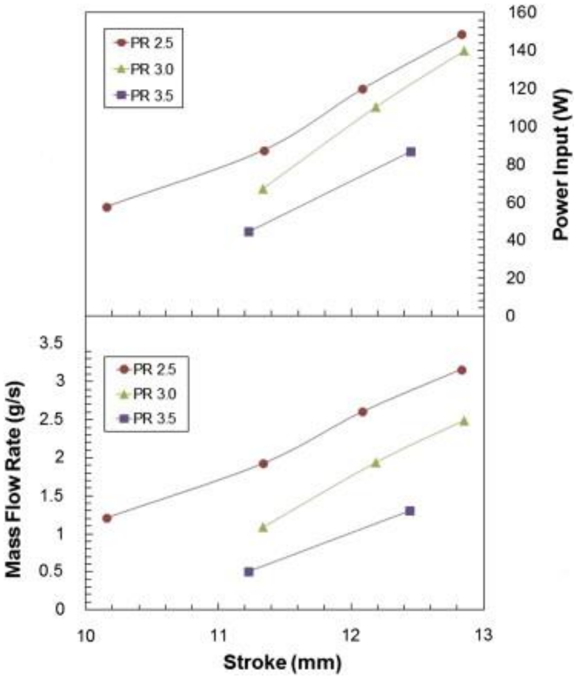


Fig. 27 Electrical power input and mass flow rate as a function of stroke for different pressure ratios using R134a (Liang et al. **[81]**)

Liang et al. **[14]** concluded that volumetric efficiency for the linear compressor is about 20% lower than the crank-drive reciprocating compressor as a result of larger clearance volume to avoid collision between from the cylinder head. To maintain a high volumetric efficiency it is desirable to have the piston run as close to the cylinder head as possible to minimize the clearance volume. Redlich et al. **[29]** also pointed out that a linear compressor (Sunpower design) with a controlled clearance volume has inherent flexibility to continuously respond to changing conditions with changes in refrigerant flow rate. By using this approach and piston controllers (by controlling the drive/excitation voltage), the cooling capacity of the linear compressor can then be modulated **[20, 38, 97, and 98]** while the cooling capacity modulation of the traditional reciprocating compressor requires a rotational speed variation.

Liang et al. **[99]** operated the Oxford-type moving magnet linear compressor with fixed minimum clearance volume in comparison with fixed datum position (zero piston offset). The results show that though volumetric efficiency was comparable, the motor efficiency was reduced by 6% with fixed clearance volume operation as more input current and subsequent electrical power were needed. Whether this phenomenon would appear in other types of linear compressor is unknown. It is recommended to compare the two operation modes for Sunpower type linear compressor as it is very commonly adopted and the motor force characteristic is different.

6.3 Compressor Losses

A simplified analysis of the linear compressor losses is given in Fig. 28. The diagram separates the compressor losses into two terms, electrical losses (or motor losses) and thermodynamic losses. The motor loss is composed of mainly the copper loss, core loss (hysteresis loss and eddy current loss) and other losses (i.e. additional eddy current losses). These losses will account for power lost in the linear motor. The shaft power generated will be driving the piston backwards and forwards. The thermodynamic losses stem from seal leakage, heat transferred (out during compression and in during expansion) and pressure drops across the valves. A systematic analysis on these losses will be sufficient to account for the motor efficiency and overall compressor efficiency. Understanding and reducing these loss mechanisms is the key to producing a more efficient linear compressor for future use.

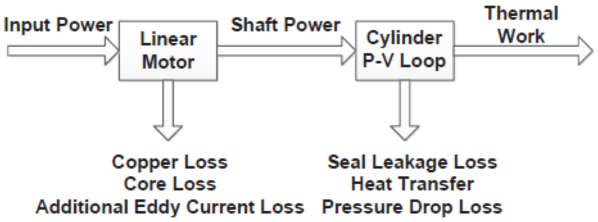


Fig. 28 Schematic of linear compressor losses (Liang et al. **[19]**)

Liang et al. **[19]** distributed the losses of a prototype moving magnet linear compressor operated at its design point (stroke of 13.4 mm and pressure ratio of 3.0). The most significant loss is the copper loss (ohmic loss, 34%). Pressure drop across the valves can be reduced with appropriate design. There is scope for significant improvements to the motor design to reduce the additional eddy current loss.

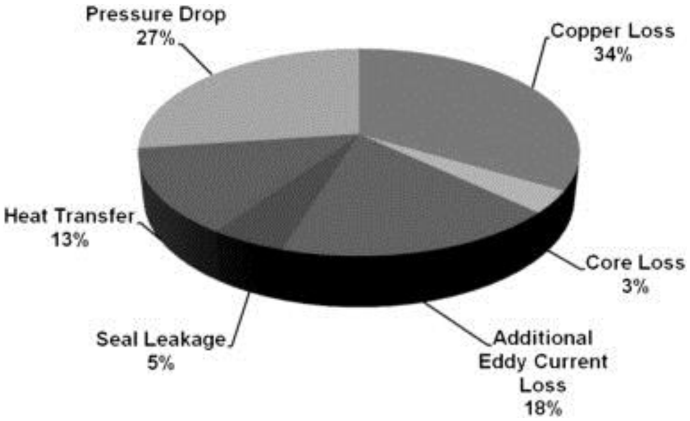


Fig. 29 Distributions of the compressor losses for the design point (Liang et al. **[19]**)

More work should be done to improve the shaft power output of linear compressor. Generally pressure drop across the valves can be easily minimized. Seal leakage can be prevented by using contact seal. The key challenge is to improve the motor loss, as described in Section 6.1.

6.4 Miniaturization

Neglecting losses and resonance, the compressor capacity is linearly proportional to the operating frequency. Therefore, capacity per unit volume or power per unit volume should benefit from high operating frequency. If flow losses are neglected, for a given mass flow rate, the required swept volume will be smaller as the operating frequency is increased.

For given suction and discharge pressures and mass flow rate $\dot{m}$, the required piston diameter D can be expressed as follow:

$$D = \sqrt{\frac{4\dot{m}}{\pi S f}} \tag{1}$$

where S is the stroke and f is the operating frequency.

Linear compressor is a resonant machine. When the operating frequency is increased, the required piston diameter is reduced. Therefore, the gas spring rate will decrease. The amount of mass m that can be resonated by the working gas is also reduced with increasing frequency as follows:

$$m = \frac{\Delta P D^2}{16\pi f^2 S} \tag{2}$$

Substituting Equation (1) into (2) will give

$$m \propto \frac{1}{f^3} \tag{3}$$

The size and weight of the linear compressor will be significantly reduced when the operating frequency is increased (shown in Fig. 30). The miniaturization of linear compressor can be achieved at much higher frequency. However, the highest frequency reported for linear compressor is 95 Hz to date but not at miniature level. Design of miniature linear compressor for higher frequency is strongly recommended for future work. Small and light linear compressor for household refrigerator will significantly allow more space for refrigeration. However, to make the resonant frequency at higher value, the suspension spring should be much stiffer. This is very challenging when coil spring is used as stiffer spring means more coils and hence large size and more weight. Resonant frequency is discussed in Section 6.5.

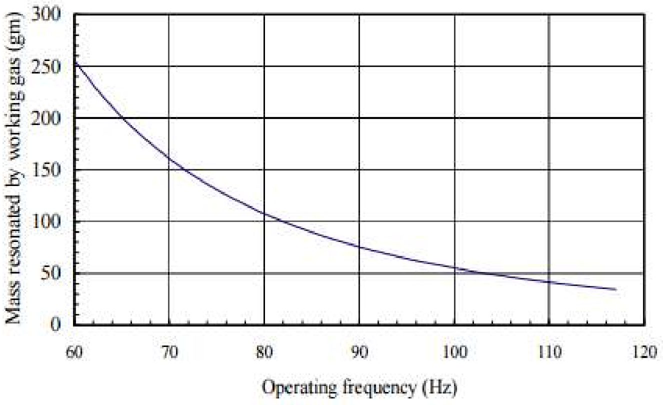


Fig. 30 Mass resonated by the working gas at varying operating frequency when pressure ratio and mass flow rate remain fixed (Unger and Novotny **[32]**)

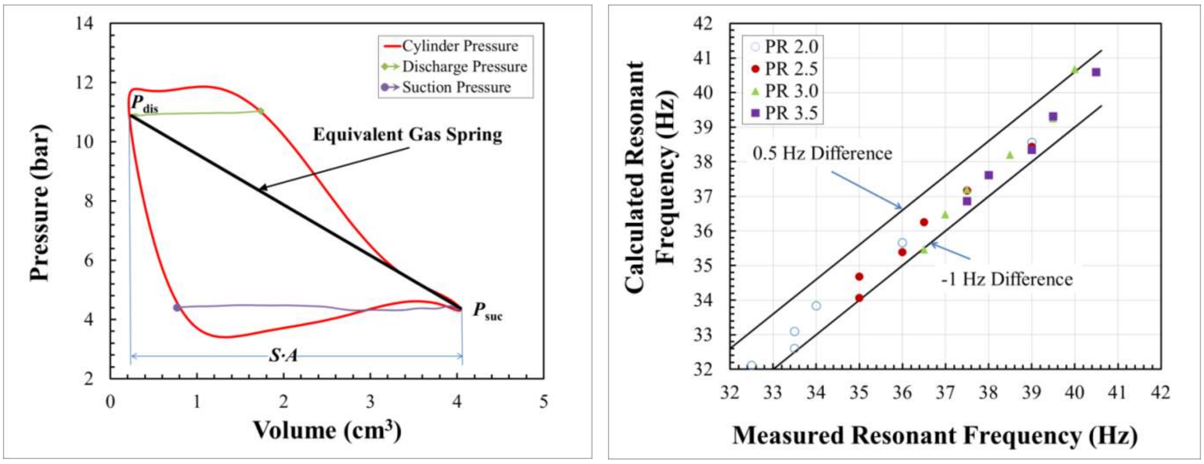
6.5 Resonant Frequency

Linear compressor can operate at resonance to reduce the input current required. The compressor spring consists of mechanical spring and gas spring. Thus the resonant frequency can be expressed as follow:

$$f = \frac{1}{2\pi}\sqrt{\frac{k_g + k_m}{m}} \tag{4}$$

where k_g and k_m are stiffness for gas spring and mechanical spring respectively.

When a linear compressor is operated at low pressure ratios (below 4.0) for electronics cooling, the gas spring can be estimated by linearizing the gas force over the compression and discharge processes (see Fig. 31). Liang **[3]** validated this simplified resonance model by measuring the resonant frequency for each operating condition.



(a) (b)

Fig. 31 P-V diagram for a pressure ratio of 2.5 showing instantaneous and equivalent cylinder gas spring for the linear compressor (a) and validation of linearized gas spring by measurements (b) (Liang et al. **[3]**)

However, when the linear compressor is operated at high pressure ratios (over 4.0), since the part of the gas spring is highly nonlinear and variable throughout the operation, it is difficult to calculate the resonance frequency. This can be solved by using a much stiffer spring, which can dominate the resonance. No accurate estimation of gas spring stiffness is needed. However, more mechanical springs will increase the size, weight and cost of the linear compressor. Dainez et al. **[100]** proposed a new approach to the linearization of the nonlinear gas pressure force and a method of adjusting the coefficients of the total spring, total damping, and equivalent continuous force. The gas pressure force was replaced by the sum of other three linear forces that compensate for the nonlinear effects of the gas pressure force as shown in Fig. 32.

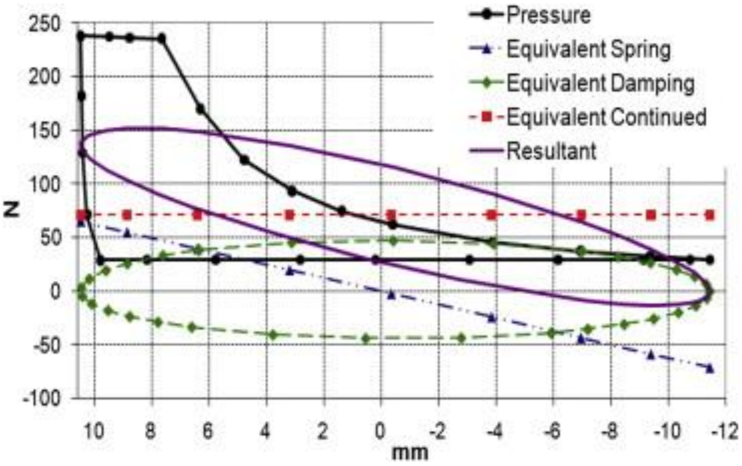
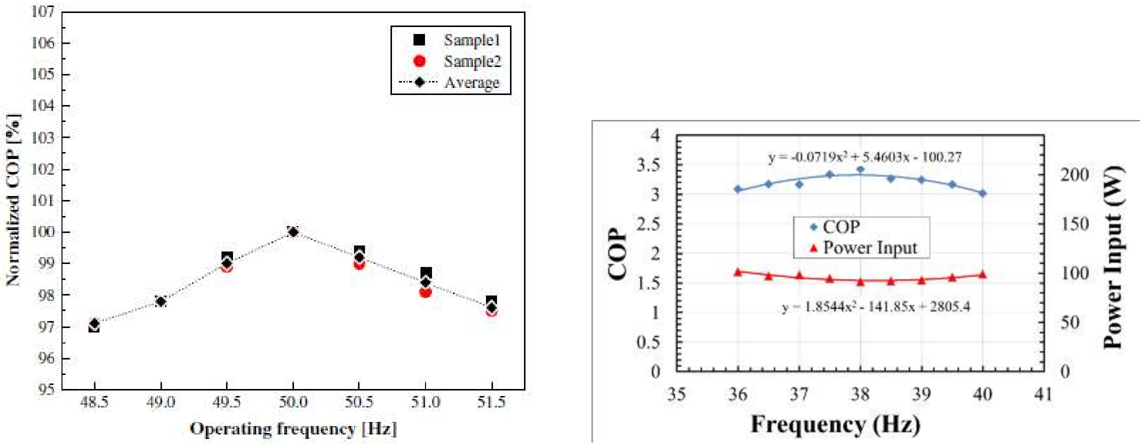


Fig. 32 Gas pressure force, equivalent forces and resultant force (Dainez et al. **[100]**)

Xia and Chen **[101]** used CFD and FEM to analyse the resonance of the linear compressor and concluded that the 'magnet spring' effect existed and affected the resonant frequency of the moving magnet type linear compressor. Minas **[102]** modelled the nonlinear dynamics of the piston as well as nonlinear effects within a linear motor for an oil-free linear compressor.

Lin et al. **[103]** proposed a resonant frequency tracking technique which was adopted by Howe and Wang **[104]** in developing a linear motor to drive a linear compressor for domestic refrigerator applications. The resonant frequency was tracked by frequency perturbation and evaluation of the motor power input, based on the fact that for given amplitude of motor current, the linear compressor system reaches its maximum stroke and maximum input and output powers at its resonant frequency.

Kim et al. **[17]** simulated the resonance and experimentally measured the effect of system resonance on the performance of a linear compressor for household refrigeration using R600. This linear compressor has a stroke of 15.2 mm, a piston diameter of 30.5 mm, and a motor constant of 93.6 N/A. The variation of the COP was about 3% when the operating frequency varied from 48.5 Hz (off-resonance) to the resonant frequency of 50 Hz as shown in Fig. 33a. Liang **[3]** measured the off-resonance performance of a linear compressor for electronics cooling using R134a. A 5% change in the drive frequency away from the resonance requires 11% extra electrical power input and reduces the COP by 12%. These off-resonance measurements verify the importance of operating the linear compressor at resonance. However, as the efficiency/frequency curves are fairly flat, it is not necessary to be very precise in choosing the operating frequency, particularly for low pressure ratio operation.



(a) (b)

Fig. 33 Off-resonance performance of linear compressors: (a) Off-resonance results of linear compressor for household refrigeration (Kim et al. **[17]**); (b) Off-resonance results of linear compressor for electronics cooling (Liang **[3]**)

It still remains unknown how instantaneously to track the resonant frequency at pressure ratios over 10 as the gas spring becomes very nonlinear. Also designing compact suspension system for higher resonant frequency is also very challenging. More work should be directed to these two areas in near future.

6.6 Piston Drift/Offset

Liang et al. **[99]** reported piston offset in a linear compressor. The problem of piston offset (or drift) is caused by the differential pressure generated across a radial clearance seal which has a fluctuating pressure on one side of it (piston-cylinder) and an almost constant pressure on the other (body), as shown in Fig. 1. The pressure differential is given by

$$\Delta P_1 = P_{1,\mathrm{m}} + P_{1,\mathrm{a}}\sin(\omega t) - P_\mathrm{b} \tag{5}$$

If there is a difference between the mean working pressure $P_{1,\mathrm{m}}$ and the body pressure P_b there will be a net axial force which is only counteracted by the mechanical springs, and this will result in a shift of the mean position of the piston. If the piston is not oscillating about the 'mechanical zero' of the springs, there will be a reduction in the useful stroke of the compressor. If there is no control strategy and if the piston offset is large, then the piston may hit the cylinder head.

Bradshaw **[2]** also reported piston drift from its datum position during operation and the linear compressor model showed that the drift decreased with the dead (clearance) volume and increased with the stroke-diameter ratio of the piston. Spoor and Corey **[105]** derived simple expressions for the time-average mass flux through a clearance seal and predicted the piston offset by assuming that the piston was acting against enclosed volumes on either side. Zou et al. **[106]** employed a formula (Choe and Kim **[107]**) to calculate the piston offset and validated the method by experiments.

The piston offset can be countered in different ways, some of which have been adopted in recent studies:

(1) Increasing the mechanical spring stiffness relative to the gas spring stiffness. This method was implemented in the LG linear compressor. Eight cylindrical coil springs with a total stiffness of 118 N/mm were used in the commercial LG linear compressor, which dominated the system resonance reported by Bradshaw **[2]**. However, by using this approach, when the linear compressor is developed for applications with high gas forces such as air conditioning compressors, the quantities of the mechanical springs and the outline dimension of the linear compressor will be much larger, as pointed out by Zou et al. **[106]**. On the other hand, more springs with a larger dimension will not be a good option when developing a linear compressor for incorporation into a miniature VCR system for electronics cooling.

(2) Superimposing a DC bias on the AC drive voltage. Using this approach, Young and Chang **[108]** developed a device and method for controlling the piston position by detecting a phase difference between the current and stroke waveforms so that the compression clearance becomes a minimum during operation of the linear compressor. However, this approach will increase the resistive (ohmic) loss (Liang et al. **[99]**).

(3) Adding mechanical and/or electromagnetic 'stops' to limit the motion of the piston. This will enable a safe operation of the linear compressor, preventing the piston from hitting the cylinder head.

(4) Control of the pressure in the compressor body, which typically requires a small bleed flow of gas from the compressor body to the suction side. Liang et al. **[99]** adopted this approach to control the piston offset by using a solenoid valve to adjust the bleed flow rate.

Cost is the major concern when considering the technique for solving the piston drift. Using bleed flow controlled solenoid valve adds extra cost. How this would affect the production cost is unknown. A cheap and low frequency (1 Hz) solenoid will significantly reduce the overall cost.

6.7 Piston Sensing and Control

The linear compressor is a free piston system, so that the cooling capacity can be modulated by the piston stroke control. Both piston stroke and piston offset require detection and control in valved compressors. The stroke is controlled by adjusting the drive voltage (excitation voltage). In order to manufacture linear compressor in large scale, then a simple, robust, and cheap control system is required with a minimum of sensors and actuators.

Liang et al. **[109]** presented a linear compressor control system (shown in Fig. 34) using a search coil. The piston stroke was detected by calculating the peak-to-peak flux linkage in relation to the measured drive voltage and current. The piston offset was proportional to an integrated modulus of the back electromotive force (emf) of the search coil. Accuracy of 0.1 mm was achieved for detecting the piston stroke.

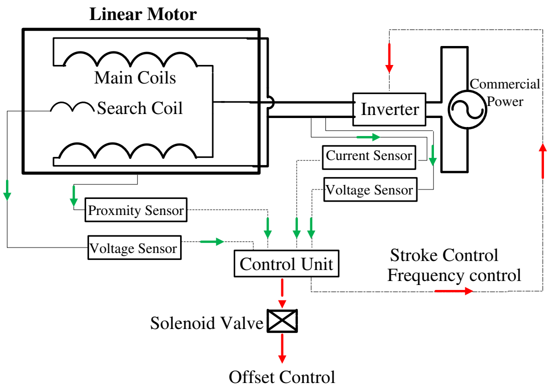


Fig. 34 Linear compressor control schematic (Liang et al. **[109]**)

Lee et al. **[36]** controlled the AC voltage to control the piston stroke of the linear compressor. Chun and Ahn **[110]** applied a PWM (Pulse Width Modulation) inverter to drive the linear motor by adjusting both voltage and frequency according to the load variation. Lee et al. **[111]** demonstrated that the cooling capacity was proportionally modulated by the under-stroke operation of the piston with a PWM inverter. Kim et al. **[20]** presented a self-capacity modulated linear compressor by tuning the LC resonance. The piston stroke was derived from the system dynamics. Thus no stroke controller is required. More studies regarding the piston control can be found in **[112, 113, and 114]**.

The key issue with position sensing and calculation is the resolution. The higher resolution it has, the higher pressure ratio the linear compressor can operate at. This will then reduce the stroke required hence the power input. More investigations on high resolution piston position sensing are very necessary.

7. Challenges and Recommended Work

Although there are already a lot of work on the modelling and measurements of different types of linear compressor, a few key issues remain unsolved. Further works on these are recommended to develop a cost effective oil-free linear compressor with high efficiency and small size.

(1) A systematic comparison between linear compressor and equivalent conventional compressor should be made experimentally in terms of efficiency, cooling capacity and impact of oil.

(2) Cost is the main challenge of linear compressor. Although rare earth material cost for linear motor can be reduced, other cost such as solenoid valve and extra manufacturing process (clean room) could add more cost to the linear compressor product. It would be interesting to see if Embraco could really manufacture their oil-free linear compressor for large scale. It is recommended to use refrigerant itself as the lubricant to reduce the production cost.

(3) Modelling the linear compressor requires complicated sub-models such as mass and heat transfer in the cylinder and the gas leakage across the radial clearance. The main concern is the very nonlinear gas spring at higher pressure ratios, which could dominate the resonance. More understanding of the gas spring will help track the resonant frequency instantaneously.

(4) Designing linear compressor for high power application such as air conditioner is very challenging. Suspension spring and motor design need a lot of studies. Linear motor needs efficiency of over 90% to be comparable with BLDC motor. This brings challenges to reduce the iron loss, copper loss and eddy current loss.

(5) Miniature linear compressor for electronics cooling with high efficiency has not been developed to date. High frequency operation at resonance is difficult as very stiff spring is needed.

(6) The key issue with position sensing and simulation is the resolution. For higher pressure ratio operation, resolution needs to be much higher. Further investigations on high resolution piston position sensing are very necessary. This will reduce the cost of the control system significantly.

(7) It is possible to design linear compressor for ammonia refrigeration system by keeping the windings outside the pressure containment. This will allow the copper and its alloy not to be in contact with ammonia.

8. Conclusions

Linear compressor is a very attractive technology for vapour compression refrigeration because of high motor efficiency, resonant operation, small size and simple capacity modulation. Linear compressor has significant advantages over conventional crank-driven compressors. Oil-free operation allows the use of micro-channel heat exchangers for miniature refrigeration system for electronics cooling.

Moving magnet type linear motor becomes the major trend due to high efficiency and compactness. Motor efficiency of linear compressor is much higher than induction motor. Though brushless DC motor (BLDC) can reach 90% efficiency, the overall compressor efficiency will be lower than linear compressor due to frictional loss with crank mechanism. Resonant frequency of the linear compressor depends on the mechanical spring and gas spring. Gas spring can be simply linearized for low pressure ratio system, e.g. for electronics cooling. For higher pressure ratio system such as household refrigeration, much stiffer spring can be used to dominate the resonance. However, this will significantly increase the overall compressor size. Piston offset can be solved though fixed dead volume (clearance) operation can increase the volumetric efficiency.

Cost is the main challenge. For electronics cooling, a miniature linear compressor makes the miniature VCR system not cost effective compared with other solutions. For household refrigeration, the major cost of manufacturing linear compressor is the material. Motor design using permanent magnets (e.g. NdFeB) can be cost effective. Contacting seal designs can be considered, as they seem to be an attractive option that could simplify manufacture and reduce material requirement (coating etc.) and hence cost. In order to manufacture linear compressor in large scale, a minimum of sensors and actuators are required. Inductive sensor for detecting the piston position can be used. With further R&D, more cost effective linear compressor products will hopefully appear in near future.

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