THE INSTITUTE OF REFRIGERATION

Cool and Straight: Linear Compressors for Refrigeration

by

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(Session 2010-2011)

To be presented before the Institute of Refrigeration at
London Chamber of Commerce and Industry, 33 Queen Street, London, EC4R 1AP
On Thursday 13th January 2011 at 5.45pm

Abstract

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 systems, with the potential for using ammonia. This paper describes the development of linear compressors, and outlines their future potential.

Introduction

Reciprocating compressors have been used for many years, and provide the power for much of our refrigeration needs. Invariably, these compressors are driven by a rotating electrical motor through a mechanism such as a crank or a 'scotch yoke'.

A lesser known area of development is the linear compressor, where the power is provided by a linear oscillating motor, directly coupled to a piston. Such machines have the advantages that all of the forces acting on the system are co-linear, so any bearings and seals have relatively light loading. From the 1950's onwards, these machines have been under development, sometimes in parallel with work on 'free piston' Stirling engines.

A typical early linear compressor was oil lubricated and driven by a moving coil motor, similar to that used in loudspeakers. These machines were resonant, with the piston mounted on a standard helical compression spring to return the piston and provide the required stiffness for the operating frequency.

One company that has been involved in these technologies over a long period is Sunpower, based in Athens, Ohio, USA. 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 ongoing [1,2].

Space Cryocoolers

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. The signal-to-noise ratio of the sensor would be enhanced if the sensor was kept at about 80 K, with the heat being rejected to the 'thermal bus' on the satellite which was at 300 K. Thermo-dynamically, the most suitable choice for this application was the Stirling cycle.

A typical Stirling cycle cooler consists of a compressor, which produces pressure pulsations, and a cold head, which contains a 'displacer piston' and heat exchangers. The displacer is synchronised with the compressor piston and is usually operated at a phase angle of about 90° to the compressor piston. Hence when the gas is expanding, much of the gas is at the cold end, and takes in heat from its surroundings, and when it is compressed, the gas has been moved to the warm end, where heat is rejected. By this means heat is pumped from a low temperature to a high temperature.

The specification for this cryocooler was:

- 1 Watt of cooling at 80 K, rejecting heat at 300 K
- 10 year life
- 230 K to 340 K survival temperature
- Survival of launch vibration (non-operating)
- Low exported vibration
- High efficiency
- NO MAINTENANCE POSSIBLE

The last requirement was the problem. A conventional single cylinder reciprocating machine has at least 5 bearings. With the 'cold end' of the cryocooler at 80 K, any oil would solidify and block the heat exchangers. Therefore the cryocooler must be oil free.

There are a variety of oil free compressors available – machines with crossheads, oil separators, ceramic pistons and metal or rubber diaphragms have all been used, but none of

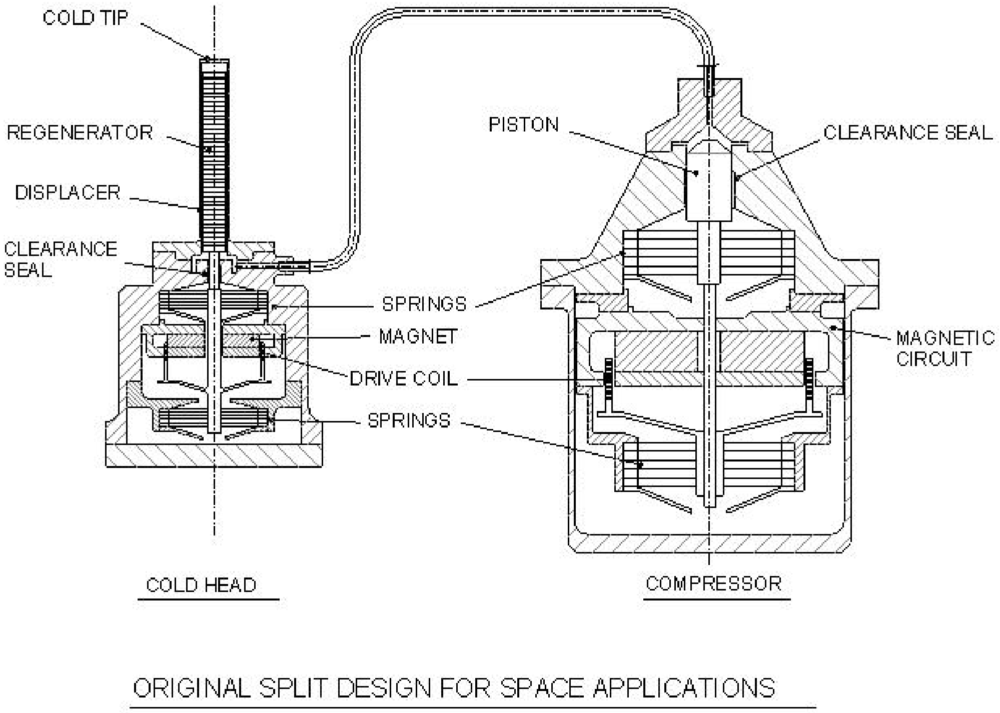

Figure 1. Early Stirling cycle cryocooler for space.

these were suitable for this application and would survive 10 years without periodic maintenance.

Early Cryocooler Development

The solution to this was provided by Dr. Gordon Davey, of the University of Oxford, who adapted a 'Pressure Modulator' developed by Oxford's Atmospheric Physics Department. The keys features of the new cryocooler (shown in figure 1) were:

- *Clearance Seals between piston and cylinder.* If the radial clearance between piston and cylinder is made small enough, the resulting leakage can be tolerated. The clearance needed is 10 – 20 µm, and this requires both piston and cylinder to have good cylindricity, and be very concentric with each other.

- *Spiral Disk Springs* are used to maintain the alignment of the piston within the cylinder, and these are typically photo-etched from thin sheet (figure 2). The spring arms, defined by the slots, act as cantilevers 'built-in' at both ends. Axially the springs are compliant, allowing the piston to move freely up and down in the cylinder, but radially they are stiff, so that the piston remains concentric. A 10 year design life at 50 Hz operation is equivalent to 1.6×10^{10} cycles, so the material used for the springs (usually austenitic stainless steel or beryllium copper) must have a 'fatigue limit', and the spring is designed so that the peak stress is safely below this limit.

Figure 2. A spiral disk spring (flexure).

- *Linear Motion.* A 'loudspeaker' type moving coil, permanent magnet motor is used to drive the compressors. With the motor, piston and springs all aligned on a common axis, there are negligible transverse forces during operation. A typical assembly suspended on spiral springs has a measured radial movement of +/- 3µm for a stroke of +/ - 5 mm.

The way these features are embodied can be seen with reference to figure 1. The compressor has a moving shaft mounted on two stacks of springs, with a moving piston in the cylinder at the top. The motor is positioned between the two spring stacks. The cold head is of similar design, but smaller, with a 'displacer' housed in a 'cold finger', the tip of which is at low temperature, and connected to the sensor being cooled. The regenerator, which stores heat as gas passes between the hot and cold ends of the displacer, is housed within the displacer.

Machines to this basic design were made by the Rutherford-Appleton Laboratory and by Oxford's Atmospheric Physics Department and flown on the ISAMS and ATSR experiments [3], and the design was also taken-up by British Aerospace (then Matra Marconi and Astrium), Lucas, Ball, Hughes/Raytheon and several other companies.

Second Generation Cryocoolers

The first generation machines were expensive to make and difficult to assemble, and there was a requirement for smaller, lower cost machines that would be suitable for non-space use (e.g. military infrared cameras). To meet these requirements, an 'Integral' cryocooler was developed at Oxford [4], which had the following characteristics:

- A single unit, with the displacer integral with the compressor
- Moving cylinder and fixed piston
- The long thin shaft of the early machines was replaced by a short fat tube acting as the moving cylinder
- Only one motor – the displacer is driven pneumatically by the pressure pulsation.
- More robust and easier to assemble than 'first generation' machines

These units were developed in partnership with the Hymatic Engineering Company (now Honeywell Hymatic (HH)) for 'tactical' and commercial markets, and there was also a transfer of technology to TRW (now part of Northrop Grumman Aerospace Systems (NGAS)), for space applications.

The Third Generation

TRW had a requirement for a compressor to drive a cold head, but with tight restrictions on the diameter and length of the compressor. To achieve this, a new moving coil motor was designed, and improvements were made to the spiral disk springs. The original design developed into a back-to-back configuration with two identical compressors acting on a common cylinder space, and this was used as the basis for the High Efficiency Cryocooler (HEC) [5], shown in figure 3.

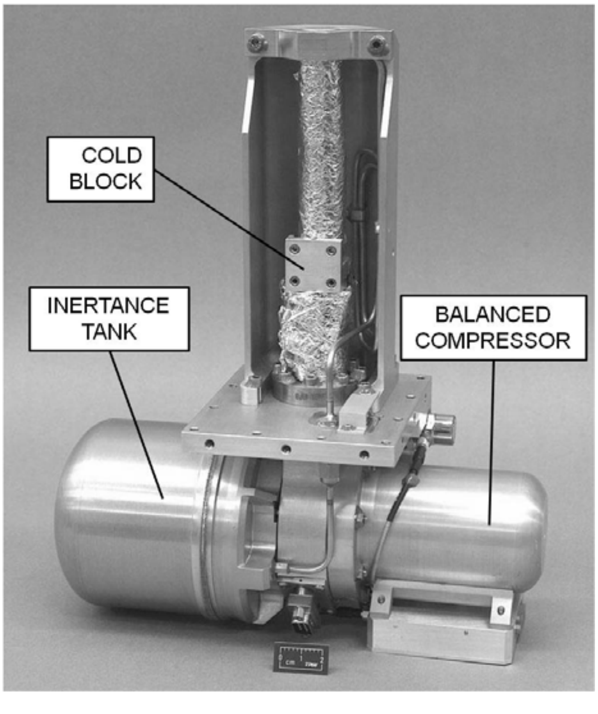

Figure 3. HEC cryocooler with pulse tube cold head and balanced compressor (NGAS).

To develop this new machine, a three way collaboration was established between Oxford University, HH and NGAS, with Hymatic producing compressors that were integrated with cold heads and drive electronics made by NGAS. To date over 40 of these 'flight' compressors have now been produced – the quantity is trivial by terrestrial standards, but is huge for this type of flight qualified space hardware.

From the original machine, which was a 6 cm^3 (2 x 3 cm^3) balanced compressor, a range of units have been developed from 26 cm^3 (the High Capacity Cryocooler – HCC) to a 0.65 cm^3 "Micro" unit. These compressors are typically mated to a 'pulse tube' cold head, which uses simple plumbing (usually an orifice and an 'inertance' tank), rather than a mechanical displacer, to give the correct pressure - volume phase relationship at the cold head.

Valved Compressors

By adding valves, linear compressors can be used to create a "DC" flow through a system, rather than being a 'pressure wave generator' required by Stirling and pulse tube systems. One application for this is in conventional vapour compression refrigeration; a similar application is for a cryogenic Joule-Thomson (J-T) cooler.

An example of the latter is a system being developed by NGAS to cool the Mid-Infra-Red Instrument (MIRI) on the James Webb Space Telescope – the successor to the Hubble. The MIRI instrument requires 65 mW of cooling at 6 K, and the system being developed consists of a three stage pulse tube cooler powered by an HCC compressor, used to pre-cool the lowest stage, which is a J-T system with a valved HEC compressor (figure 4).

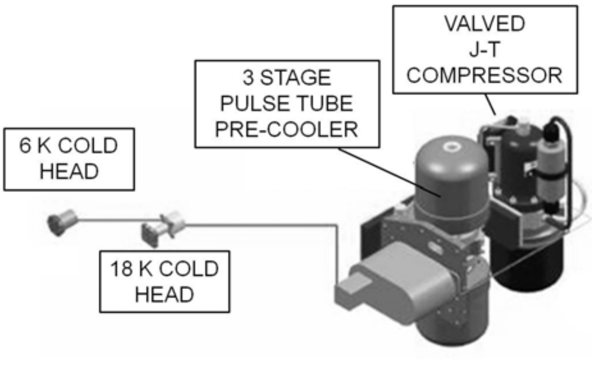

Figure 4. The proposed cooling system for the MIRI instrument on the James Webb Space Telescope (NGAS).

Two prototype valved compressors have been built by Oxford [6] and HH, and are being tested on the complete J-T system by NGAS. The 'flight' compressors will be built by HH in 2011.

Benefits of Oil Free Linear Compressors

There are several benefits of oil free linear compressors.

- The absence of oil makes these compressors suitable for use with high purity and medical gases, where oil cannot be tolerated.
- Finding suitable combinations of oil and refrigerant has been one of the major problems in the development of new refrigerants. Elimination of oil widens both the choice of refrigerants, and their operating temperature range.
- Eliminating the need for oil return reduces constraints on pipe sizing and will lead to a reduction in pressure drop losses.
- The presence of oil films on the inside of heat exchangers reduces heat transfer coefficients, and limits the range of heat transfer geometry that can be used (see 'Computer Cooling' below).
- Small linear oscillating motors can be made economically with motor efficiencies of 90%.
- Elimination of cranks and bearings gives a significant reduction in mechanical friction losses.

Disadvantages of the Technology

The lack of oil leads to increased gas leakage in two areas:

- Between piston and cylinder
- Between valve and valve seat (though oil will also tend to inhibit the opening of valves due to both inertial and surface tension effects; delayed opening of valves is effectively a loss)

One of the main advantages of crank-driven compressors is that the position of the piston is well defined by the mechanism, and clearance volumes approaching zero can be achieved.

In a high efficiency linear machine, the piston operates resonantly in order to minimise the drive current. Resonance is determined by the moving mass and by spring stiffness, which has two components, the mechanical springs, and the 'gas spring' effect of the compression process. In a typical 'Oxford' type (clearance seal/disk spring) machine, the mechanical spring rate is about 25 to 35% of the total spring rate.

Gas springs do not provide a definite 'centring force' in the same way that a mechanical spring does. Instead the piston will respond to the pressure difference across it, with the piston motion and position determined by the sum of pressure, mechanical and electromagnetic forces acting on it. All of these are periodic, and some of them can be very non-sinusoidal, especially in a compressor with valves.

A further complication arises from the clearance seal. The leakage flow in the small clearance between piston and cylinder will be laminar, and the volumetric flow rate through the clearance is a function of the pressure difference between the ends of the seal. The 'motor' end of the seal is nominally at a constant pressure, while the 'cylinder' end experiences the varying cylinder pressure. Within the seal, heat transfer is very good, so the gas flow tends to isothermal; consequently the density of the gas in the clearance varies with the pressure.

The net effect of this is as follows:

- when the cylinder pressure is higher than the 'motor' pressure, the mean gas density in the seal is high;
- when the cylinder pressure is lower, the mean density is lower
- if the 'volumetric' flow rate is equal during each of these half-cycles, there will be a net mass flow from the 'cylinder' space to the 'motor' space
- The pressure in the 'motor' space will rise, and that in the 'cylinder' space will fall
- The resulting pressure difference will drive the piston towards the cylinder head.

This phenomenon is known as the 'DC offset' effect, and can be countered in a variety of ways:

- Increasing mechanical spring stiffness relative to the gas spring stiffness
- Superimposing a DC bias on the AC drive voltage
- Adding mechanical or electromagnetic 'stops' to limit the motion of the piston
- Control of the pressure in the 'motor' space, which will typically require a small 'bleed' flow of gas.

The cumulative effect of all of these is that in some machines there can be limit on the pressure ratio that a single stage compressor can produce, and there may be small parasitic losses arising from the control of the 'DC offset'. These can be serious disadvantages for some applications.

Recent Linear Compressor Development

The most noticeable recent development is by the Korean based LG company. They have licensed Sunpower's linear technology, and have now been marketing linear compressor systems since 2002 [7].

Interestingly, 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 which has long been a feature of the Sunpower pedigree. It would be interesting to see how much of the Sunpower 'heritage' technology is actually used in the latest LG compressors.

A very recent development has been made by the Brazilian company Embraco, who have recently announced a new oil-free linear compressor, also designed for R134a and R600a. The picture distributed with the press announcements [8] shows a curious dog-bone shaped pressure vessel, which bears little relation to the diagrams in a seemingly related recent patent [9].

Computer Cooling

Computers have reached the stage where performance is being limited by the heat generated in CPU chips. Because they are very small, the heat flux required to cool them is higher than can be obtained with a forced convection heat sink clamped to the top surface.

Suitable heat fluxes can be obtained by evaporative cooling, especially if a very fine extended heat transfer surface can be formed into the surface of the chip, which would become the 'evaporator' of a conventional vapour compression refrigerator. The problem with an 'off-the-shelf' system is the presence of oil, which circulates with the refrigerant, and would quickly find its way to the fine extended surface, which it would block.

Oil free compressors provide a solution to this problem – the clearance seal/spring system requires no lubrication and produces no debris that would foul the extended surface of the evaporator. Oxford has recently finished a three year project, in collaboration with Newcastle University and London South Bank University to develop this technology.

Moving coil compressors are too expensive to be used in applications such as these. The Sunpower and Embraco linear compressors have a moving magnet motor, but the magnet in these is in the form of a thin tube, which is also not simple to embody. The compressor produced at Oxford includes a new low cost moving magnet linear motor, which features cheap silicon-iron laminations and conventional windings (similar to those in a standard rotary motor) which are positioned outside the pressure containment (figure 5 and 6). The magnets are small cuboids, and these are within the pressure containment [10].

Future Work: Ammonia and Higher Speeds?

An advantage of keeping the windings outside of the pressure containment is that it becomes possible to design a compressor with no copper or copper alloys in contact with the working fluid, and this has obvious benefits for use of ammonia as a refrigerant. A recent paper by Prof. Palm of KTH in Sweden commented that "The main obstacle for introducing this technology [ammonia] commercially is the lack of components. Particularly, there seem to be no hermetic or semi-hermetic compressor available in this size range" [11]. The new

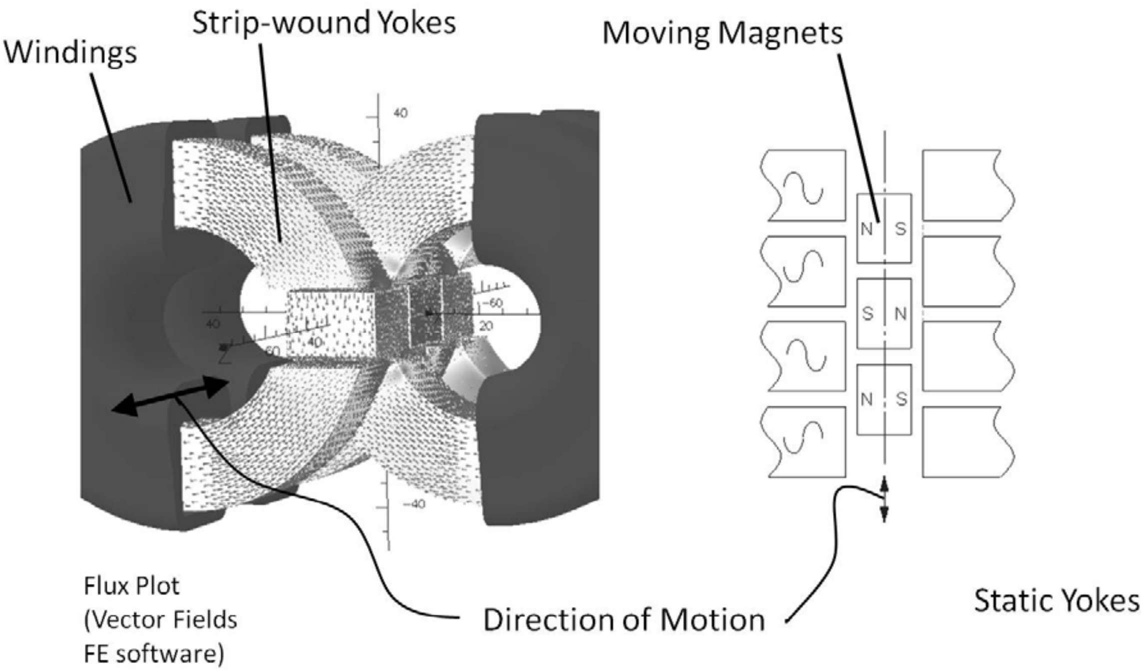

Figure 5. Novel moving magnet linear motor.

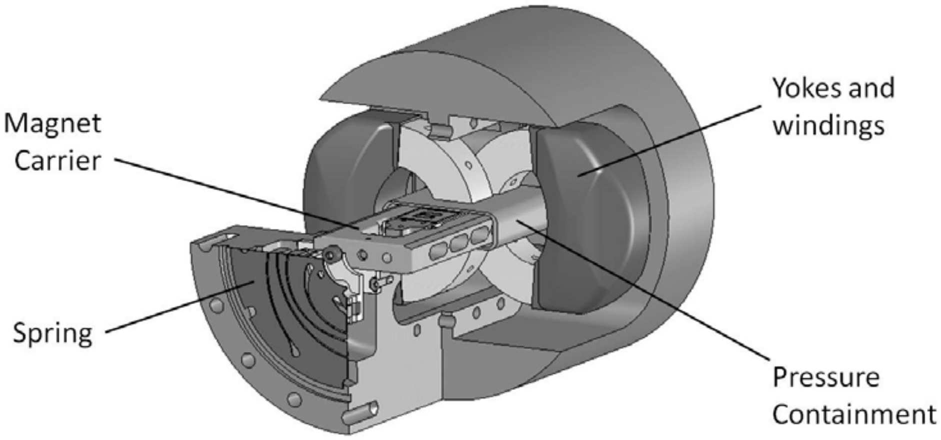

Figure 6. Moving magnet motor in a linear compressor.

Oxford design of compressor is an obvious starting point for developing a small ammonia compressor.

Another area where linear compressors have a potential advantage over rotary machines is in the potential for high speed operation; the higher the frequency, the smaller the swept volume needed for a desired flow rate. The design of rotary machines becomes increasing difficult at high speeds due to centrifugal stresses and bearing loads. Stresses also increase in linear machines, but as the main loads are all axial, it is relatively easy to design for high speeds.

The two main problems with high speed operation are:

- Achieving resonant operation: this would require stiffer mechanical springs, or possibly an auxiliary ‘gas spring’. The latter approach is currently being studied by Oxford with regard to space cryocooler compressors.
- Valves. To avoid throttling, very fast acting valves are required, which may preclude the use of traditional reed valves.

It is with interest that we note the paper given by Embraco in September 2009, which models the reed valves proposed for a 0.52 cm^3 compressor operating at 350 Hz [12]; they also see the potential for high speed compressors.

Conclusions

After a long period of development, Linear Compressors are now becoming available in the market place, where have the potential for increased performance and improved controllability. There is clearly scope for further development, particularly with respect to oil free operation, and use with ammonia and other novel refrigerants.

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