Development of a permanent magnet free piston compressor

by

Dyke W. Monyane

Thesis Presented for the Degree of
Magister Technologiae
in the Department of Electrical Engineering
Cape Peninsula University of Technology
November 2005

Declaration

I, Dyke Wellington Monyane, declare that this thesis is my own work. I have not submitted it for any degree at this institute or at any other institution. All the literature used in this thesis has been fully referenced.

Therefore, I hereby submit this thesis as part of the Magister Technologiae in Electrical Engineering at the Cape Peninsula University of Technology.

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DW Monyane
14th November 2005

Acknowledgements

I would like to acknowledge the following people, who contributed to the success of this work.

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on March 17, 2006, in partial fulfillment of the
requirements for the degree of
Magister Technologiae

Synopsis

There is a high demand for refrigerators in South Africa, as revealed by the Eskom TSI market survey. Refrigerators are found to be expensive because compressors are imported and compressors cost 45% of the total budget of a refrigerator. For this reason a project was undertaken to develop an affordable refrigerator but this was unsuccessful owing to expensive compressors. The compressor consists of an induction motor coupled to the compression unit via a crankshaft. In this thesis a novel permanent magnet free piston compressor is designed and constructed by using a linear motor topology. The permanent magnets that are used are the Neodymium Iron Boron (NdFeB) with a high energy density of $278.7\mathrm{kJ/m^3}$ and a coercive force of 955kA/m. Backing iron discs are attached at each end of the magnet to contain all the flux in a semi closed loop. The driving coils are embedded in a plastic enclosure through a vacuum casting process. The coils are wound in such a manner that a current in one polarity causes a force in one direction, and vice versa. This is a point of ingenuity of the design because it allows simple and cost effective driving circuitry, whereas most linear motors require many phases with sensing and control circuitry to drive the coils in phase. The driving circuit consists of a full bridge inverter and the driving signals generated, using an Atmel microcontroller. The permanent magnet is used as both a secondary for a linear motor and as a piston for the compressor. The compressor is double acting, which means it compresses in one chamber while extracting air in another chamber and vice versa when the direction of the piston is changed. The stroke length is maximized because longer strokes result in maximum volumetric efficiency. It must be stated that a novel permanent magnet free piston compressor was successfully designed, although with limited tests since the main objective of this thesis was a proof of concept. The compressed air is demonstrated by blowing bubbles in a bottle of water. The concept was proved adequately at low pressures. The final chapter discusses further work to take this concept further on how to yield higher pressures/forces. The patent for this project has been filed.

Contents

List of Figures

Abbreviations and Symbols

Abbreviations

COP	Coefficient of Performance
LCDR	Low Cost Domestic Refrigerator
PMFPC	Permanent Magnet Free Piston Compressor
p-h	pressure-enthalpy
SDT	Saturated Discharge Temperature
SST	Saturated Suction Temperature
Q	Heat Energy
TDC	Top Dead Centre
BDC	Bottom Dead Centre
BHmax	Maximum energy product
NdFeB	Neodymium Iron Boron
SmCo	Samarium Cobalt
AlNiCo	Aluminium Nickel Cobalt

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Symbols

L	Inductance
C	Capacitance
R	Resistance
$\dot{m}$	Mass flow rate
v	specific volume
η	Efficiency
h	Enthalpy
S	Entropy
p	Pressure
v	Volume
C_p	Specific heat at constant pressure
H_{fg}	Heat of evaporation
T	Temperature
D	Diplacement
C_{vol}	Clearance volumetric ratio
ϕ	Magnetic flux
B	Magnetic flux density
A	Area
N	No. of turns
H	Magnetic field strength
μ_o	permeability of vacuum
μ_r	relative permeability
P	Power
V	Voltage

Chapter 1

Introduction

1.1 Objective

The main aim of this thesis was to invent, devise and develop a new kind of refrigerator compressor, which could be manufactured for less than current compressor designs. This thesis will discuss the design and development of a novel compressor from the simple form of Lenz's law, through a stage where it is developed to pump air.

1.2 Background

The Eskom electrification programme has provided electrical power to over 2 million households over the last eight years. However, the main use of electricity in these homes has been for lighting and television. Research has revealed that electricity was not used to its full capacity, as it was found that other electrical appliances were too expensive to purchase.

Eskom has therefore identified a need to develop affordable electrical appliances for low-income households in order to realize the complete benefits of electricity. A survey was undertaken by Eskom Enterprise (TSI) in order to ascertain what further appliances people were interested in. The results indicated that a refrigerator was preferred; however, its cost was a major barrier in these households [12].

Table 1.1: Specifications of a desired refrigerator by Eskom

Refrigerator Size	Volume: 100 litres(fridge volume=77.5l and freezer volume=22.5l
Power Source	220V, 50Hz and current $\leq$ 1.25A
Compressor	Power (W):96, Displacement 4.33cm^3, 83$Kcal/h$, one year guarantee
System Performance (COP)	$2.5 \leq COP \leq 5.0$
Refrigerant Gas	R134a
Evaporator Temperature	-1 °C $\leq$ Tevap. $\leq$ -35 °C
Condensing Temperature	$\leq$60 °C
Operating Temperature	4 °C inside the fridge and $\leq$-18 °C freezer
Insulation Material	Polyurethane recommended but should be CFC free

Local and international refrigerator manufacturers were approached to assist in the development of an affordable refrigerator for the low income South African market. The specifications of this refrigerator were as tabulated in above table.

Godrej-GE Appliances in India was contacted, based on the offer made to TSI in 1999 to supply 150l refrigerators at a cost of approximately ZAR900. Owing to freight rates, customs duty,and documentation, the cost for one refrigerator would be ZAR2500 when it landed in South Africa. The imported Indian refrigerators were, therefore, not regarded as feasible.

In 2002, a project was undertaken by the Energy Technology Unit under the CIR at the Cape Technikon to develop a Low Cost Domestic Refrigerator (LCDR) of 150 litres for the lower income homes, with a maximum budget of ZAR800 per unit, as per Eskom's specifications[12].

Although many of the components of the refrigerator were optimized and even built from scratch (e.g. the condenser unit was built at the Mechanical Engineering Faculty of the Cape Technikon), it was found that the most expensive part of the refrigerator was the compressor. Research showed that the compressor alone costs between 45% and 50% of the total cost of a refrigerator because they have to be imported, which makes the target cost of ZAR900 unrealistic.

Hence, the compressors were investigated to ascertain why they are that expensive. As a result, a preliminary investigation was conducted, whereby scrap compressors were opened in the Department of Mechanical Engineering at the Cape Technikon, in order to study existing designs and materials that make up the system. The electric motors that were present within the sealed compressors unit were examined. The result of this preliminary investigation was that existing compressors are neither easy to optimize nor to reproduce cheaply, owing to their complex machining and expensive materials used. These compressors are already produced in large volumes, which means the economies of scale would be impossible to improve upon.

This has forced the research team to re-examine the architecture of the compressor by basing the research on affordable materials and emphasising simplicity in construction.

1.3 Hypothesis

The researcher believes a functional working unit can be obtained to replace the conventional compressor used in a refrigeration system and that this unit can be developed to an extent, where it can be manufactured at a relatively cheap cost.

1.4 Novel linear compressor

The fundamental aim of this project was to design a new type of compressor based on novel linear motor topology. The Linear Motor is a rotating motor flatly opened. Instead of producing a rotating torque as in cylindrical machines, it produces a linear force. The speed is determined by the winding design and supply frequency. Unlike conventional compressors, where the rotating motion of the motor is converted into reciprocating motion, the linear motor produces reciprocating motion directly. The motor and compressor form one part, with no coupling required.

It is almost a general principle that when the topological features of an electric machine is modified, such as developing a linear motion machine when developed from its rotary counterpart, the operating characteristics and the design criteria of a new machine change considerably. For example, as a result of the topological changes in the magnetic circuit of a machine, new electromagnetic phenomena come into play that cannot be fully explained by conventional rotating machine theory. Consequently, older methods of analysis have to be modified and at times new theories have to be developed.

The idea of designing a linear compressor originated from Faraday's Law which states that any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, a voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field and rotating the coil relative to the magnet.

Therefore, from Faraday's Law it can be deduced that if the magnet is pushed through a coil of wire, an emf will be generated. The process should be reversible if the voltage is applied in a solenoid with the magnet inside, as the magnet will be pushed or pulled away from the coil and if the applied voltage alternates, the magnet will be pushed backward and forward.

A patent search was conducted [24] [9] [29] [15] [35] [22] and it appeared that this idea was patentable. A patent was filed on the 18 May 2005. The reference number for the application is V16803.

1.5 Thesis overview

The thesis is divided into several chapters. The chapters follow each other logically to show progression and completion of the design. Chapter 1 is an introductory description, which outlined the objectives and goals of the thesis and states the problem statement as well as the background of the project and why the project was initiated.

Chapter 2 - 5 contains the literature review, which is a discussion and analysis of the information obtained from journals, library databases, textbooks and Internet sources, in order to gain knowledge of refrigeration, linear motors, rare earth magnets (permanent magnets) and plastic technology (casting, injection molding and machining).

Design implementation will be discussed in chapter 6 followed by a circuit analysis in chapter 7. Conclusions and future work will end the thesis.

Chapter 2

Refrigeration

Preserving food has always been a necessity of [mankind] sic [2]. Keeping food fresh by cooling it, i.e. by slowing down the growth of bacteria, can be a fairly difficult task. Until the invention of refrigeration, the only means of lowering the temperature was by harvesting and storing blocks of 'natural' ice grown in winter or by evaporative cooling. At present, most domestic refrigerators use a vapour-compression refrigeration cycle.

Refrigeration deals with the transfer of heat from a low temperature level at the heat source to a high temperature level at the heat sink. Refrigeration plays an important role in developing countries, primarily to preserve food, medicines and for air conditioning. Examples are:

- Domestic:

Food and drink storage;

- In retail trades:

Sale of fresh foods, fish and cold drinks;

- In agriculture and dairies:

Removal of field heat immediately after the harvesting of crops, storage of fruits, vegetables, milk, meat, and cooling during the transport of products;

- Health clinics:

Storage of blood, vaccines and medicines; and

- Buildings, computer installations:

Air conditioning and temperature regulation.

2.1 Previous refrigerators

There are different types of household refrigeration which are suitable for southern African countries, and the two basic types of refrigerating systems are Vapour compression, which is commonly used, and Absorption, which is gaining popularity because of its ability to use low grade heat, such as low pressure steam or solar energy which produces a cooling effect [2]. It does, however, require a continuous supply of power.

Thermoelectric, Stirling and Thermoacoustic cooling technologies, are the types that are also available but are still in the process of being researched for household refrigeration. These methods are not commercially available.

The environmentally friendly solar household refrigerator, which used Stirling cycle technology, is under development at Global Cooling Inc. [7].

2.2 Refrigeration fundamentals

The second law of thermodynamics states that heat cannot flow from a body of low temperature to another body at a higher temperature, unless work is being done to supply energy to the system. All conventional refrigeration cycles require that power be introduced into the refrigeration system in order to compress gas or vapour from a low suction pressure to a high condensing pressure, creating a temperature lift [13].

2.2.1 Refrigerant

Refrigerant is a fluid that is used inside the refrigeration system to transfer heat. For the purposes of this study, only refrigerant HFC134a (R134a) will be considered as other refrigerants such as CFC12 (R12) and HCFC22 (R22) will be phased out as a result of subsequent revisions of the Montreal Protocol owing to their danger to the environment [32].

Table 2.1: The properties of R134a

Chemical Representation	Tetrafluoroethane (CF_3CH_2F)
Molecular Weight	02.03 kg/ kmol
Critical Temperature	374 K (101 °C)
Critical Pressure	40.7 bar
Saturated Liquid at 300K	Specific Heat (Cp) = 1.434 kJ/ kg. K

Refrigeration systems, which use vapour, depend on the fact that a vapourizing liquid requires relatively large amounts of heat and that the temperature at which vapourization and condensation take, place depends upon pressure. By regulating the vapourization and condensation pressures, refrigerant temperatures can be controlled for useful cooling.

Desirable characteristics of refrigerants

- Non-flammable to reduce fire hazards.
- Non-toxic to reduce potential health risks.
- Large heat of evaporation to minimize equipment size and refrigerant quantity.
- Low specific volume in the vapour phase to minimize compressor size.
- High heat transfer coefficient.
- Non-stratospheric ozone destroying properties.
- Low liquid phase specific heat to minimize the heat required when subcooling the liquid below the condensation temperature [11].

2.2.2 Refrigeration cycle

The properties of refrigerants can be listed in tables or they can be shown in a graph. There are a number of types and arrangements of property diagrams. The one that is most useful and used most often in refrigeration work is called pressure-enthalpy (p-h) or Mollier diagram. Figure 2-1 shows what a basic refrigeration system would look like when traced on the pressure-enthalpy diagram.

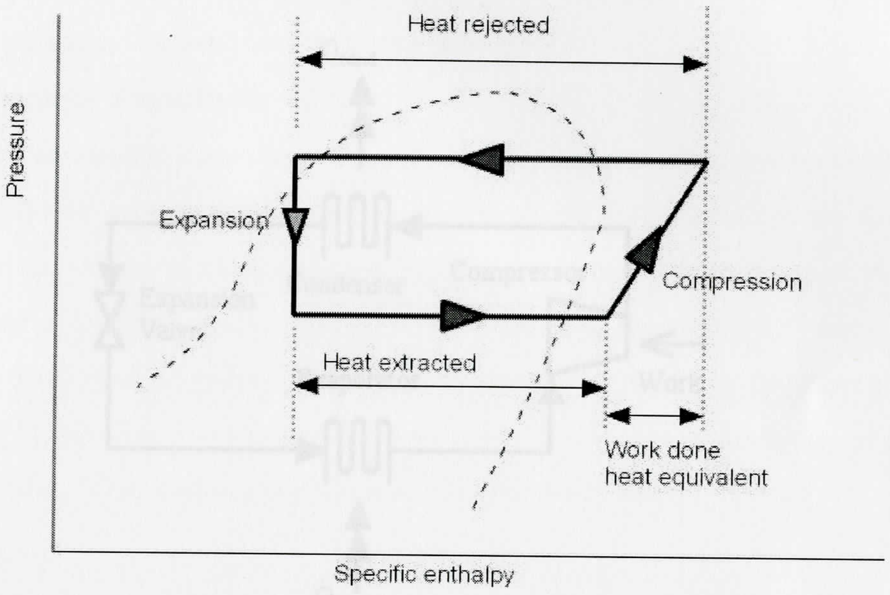

Figure 2-1: p-h diagram for a vapour compression cycle

The vapour-compression refrigeration cycle typically consists of a compressor, a condenser, an expansion valve and an evaporator. Enthalpy is defined to be the sum of the internal energy E of matter plus the product of the pressure p and volume V, using the symbol H for the enthalpy. Enthalpy is then a precisely measurable state variable, since it is defined in terms of three other precisely definable state variables:

$$H = E + pV \tag{2.1}$$

Enthalpy is a quantifiable state function, and the total enthalpy of a system cannot be measured directly; the enthalpy change of a system is measured instead:

$$\Delta H = H_{final} - H_{initial} \tag{2.2}$$

The basic refrigeration cycle, as illustrated in Figure 2-2, entails four steps:

- **Step 1- Evaporator**

A cool, low pressure liquid refrigerant is brought into contact with the heat source, which is the medium to be cooled. The refrigerant, being at low pressure, absorbs

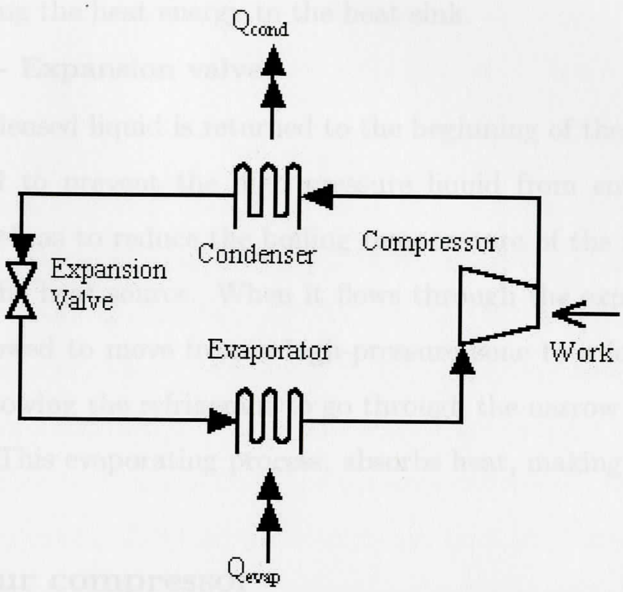

Figure 2-2: Operation system for refrigeration cycle

heat from the medium being cooled and boils, producing a low pressure vapour because of saturation conditions. The heat exchanger used for this process is called the Evaporator.

- **Step 2- Compressor**

The compressor is the central component of every refrigerator. It has to be supplied with electrical energy in order to produce mechanical energy to pump the refrigerant so that the desired cooling effect can be obtained. The addition of the shaft work by the compressor raises the pressure of the refrigerant vapour. Increasing the gas pressure raises the boiling and condensing temperatures of the refrigerant. Once the refrigerant gas has been sufficiently compressed, its boiling point temperature is above the temperature of the heat sink, which is the higher temperature medium.

- **Step 3- Condenser**

The high pressure refrigerant gas, which carries the heat energy absorbed at the evaporator and the work energy from the compressor, is pumped to a second heat exchanger called the Condenser. Because the refrigerant's condensing temperature is higher than that of the heat sink, heat transfer takes place, condensing a refrigerant from high pressure vapour to a high pressure saturated liquid. The heat source has been cooled by pumping the heat energy to the heat sink.

- **Step 4- Expansion valve**

The condensed liquid is returned to the beginning of the next cycle. Its pressure must be reduced to prevent the high pressure liquid from entering the low pressure evaporator, as well as to reduce the boiling temperature of the refrigerant to below the temperature of the heat source. When it flows through the expansion valve, the liquid refrigerant is allowed to move from a high-pressure zone to a low-pressure zone, which is achieved by allowing the refrigerant to go through the narrow diameter, as it expands and evaporates. This evaporating process, absorbs heat, making it cold.

2.2.3 Vapour compressor

A compressor can be considered as a vapour pump. The most common types are the reciprocating, rotary and scroll compressor. Single-phase AC motors, such as the capacitor start motor and the split-phase motor, drive these compressors. The three-phase motors are also used but are not applicable for domestic use, as the majority of households are supplied with a single-phase source.

2.2.4 Reciprocating compressor

Reciprocating compressors are commonly used for small refrigerators (domestic) .A piston in a cylinder is used to compress the refrigerant. The piston is linked by a connecting rod, which is driven by the crankshaft from an electric motor. Only hermetic compressors are considered in this study, as these are used for domestic refrigeration.

The compressor produces the pressure differential required by the system. It must absorb vapour from the evaporator and discharge it to the condenser at a much higher pressure. When the piston is at the bottom of its stroke, the cylinder is full of refrigerant at a pressure equal to the system suction pressure. As pressure builds up, the cylinder volume is decreased and the pressure inside the cylinder is increased. The pressure continues to build until the cylinder pressure is high enough to overcome the high-side pressure that is holding the discharge valve closed. Further upward movement of the piston then causes the discharge valve to open because of the high cylinder pressure. The refrigerant is discharged to the condenser until the piston reaches the top of its stroke.

At the top of the piston stroke, there is still a small clearance volume (S_o) left. Practically, a clearance volume cannot be zero but in order to increase efficiency, it must be kept as small as possible [28]. When the piston starts on its way down, the high pressure refrigerant that was trapped in this clearance volume re-expands to fill the increasing cylinder volume and the pressure inside the cylinder falls. When the cylinder pressure drops below suction pressure, the pressure difference causes the suction valve to open. Further movement of the piston towards the bottom of its stroke causes refrigerant vapour to be absorbed from the evaporator into the cylinder through the suction valve. The four stages of the compression cycle described here are referred to as compression, discharge, expansion and suction, as shown in Figure 2-3.

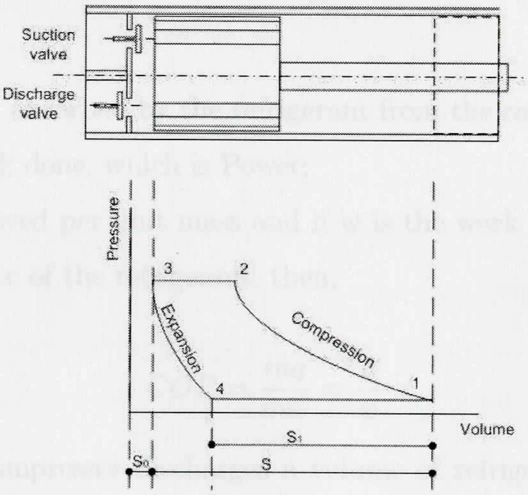

Figure 2-3: The movement of a piston in a reciprocating compressor

2.2.5 Compressor Design

When a compressor is designed, the compressor capacity is determined by the volume of refrigerant pumped. The capacity will be determined by the piston and cylinder dimensions, length of the stroke, the number of cylinders and the speed (frequency / cycles per second) of the compressor.

Compressor capacity is the measure of a compressor, which causes refrigeration and it depends on two factors:

- Mass flow rate (kg/s): The transfer of a mass of refrigerant per unit of time. The mass flow rate is the product of density, velocity and area.
- Refrigerating effect (kJ/kg): The heat absorbed by the refrigerant from the refrigerated space.

The purpose of the refrigerator is to remove heat from the cold region, while requiring as little external work as possible. A measure of the efficiency of the device is therefore:

$$COP = \frac{Q}{W} \tag{2.3}$$

where

Q is the rate of heat absorbed by the refrigerant from the refrigerated space;

W is the rate of work done, which is Power;

If q is the heat removed per unit mass and if w is the work done per unit mass and if $\dot{m}$ is the mass flow rate of the refrigerant, then,

$$COP = \frac{\dot{m}q}{\dot{m}w} = \frac{q}{w} \tag{2.4}$$

Theoretically, the compressor discharges a volume of refrigerant equal to the total volume displaced by each stroke of the piston. The piston displacement may be calculated as:

$$d = \frac{\Pi b^2}{4} l \tag{2.5}$$

where

d is the piston displacement;

b is the bore (diameter) of the cylinder;

l is the stroke length; and

Therefore, the displacement of the compressor may be calculated as:

$$D = \frac{\Pi b^2 l}{4} \times n \times f \tag{2.6}$$

where

D is the compressor displacement;

n is the number of cylinders; and

f is the compressor frequency.

Theoretically, the amount of refrigerant pumped equals the compressor displacement but the part of the downstroke is wasted in allowing re-expansion rather than allowing fresh vapour to be drawn into the cylinder. The ratio of the actual volume of vapour pumped divided by the calculated volume is called the Volumetric Efficiency of the compressor, which is why it is important when designing a compressor to keep the clearance volume as small as possible.

Compression ratio

The compression ratio of a compressor is defined as the absolute discharge pressure divided by the absolute suction pressure. A system should not be designed that requires a compression ratio higher than 10:1 [37]. Higher compression ratios cause too much work to be done on the refrigerant, while a high refrigerant temperature will result. This may cause equipment failure, due to the infirmity of compressor parts.

Compressor power

This is a theoretical power required to drive a compressor. If the compression can be represented as a polytropic process, the compressor power will only depend on the saturated discharge temperature (SDT) and the saturated suction temperature (SST), independent of the level of superheat. Superheat is the amount of heat added to the liquid to make it saturated and to change states. This conclusion is reached from the following analysis. The work per unit mass (w) required to compress refrigerant from the suction conditions to the discharge conditions in a polytropic process (i.e. pv^n=constant), is given by Equation 2.7

$$w = \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \tag{2.7}$$

where

w is the compressor work per unit mass;

n is the polytropic coefficient;

P_1 and P_2 are suction and discharge pressures (corresponding to the suction and discharge temperatures, respectively); and

v_1 is the suction specific volume of the suction gas.

The compressor power is

$$POW = \frac{w\dot{m}}{\eta_{motor}} \tag{2.8}$$

where

$\dot{m}$ is the mass flow rate; and

η is the motor efficiency.

The mass flow rate is related to the compressor volume displacement rate by volumetric efficiency, which can be expressed as Equation: 2.9

$$\eta_{vol} = \frac{mv_1}{D} = 1 + C_{vol} - C_{vol} \left(\frac{P_2}{P_1} \right)^{\frac{1}{n}} \tag{2.9}$$

where

η_{vol} is the compressor volumetric efficiency;

C_{vol} is the clearance volumetric ratio; and

D is the compressor displacement rate.

Influences of compressor design on efficiency

The quantity of gas, which enters the cylinder is represented by 1-4 in Figure 2-3, where S_1indicates the volume of gas induced. When the larger S_1 is compared with S, the smaller the compressor can be built [25]. This implies that a relatively short stroke compared with a large piston diameter, results in a larger clearance volume, thus decreasing volumetric efficiency η_{vol} and increasing the piston leakage. A short stroke length results in a shorter life span of the valves and a complex valve design. S_1/S is also defined as volumetric efficiency η_{vol}. A long stroke length and small diameter increases volumetric efficiency and as a result, the stroke should be maximized and the diameter minimized.

Chapter 3

Linear motor

3.1 History

The idea of a linear induction motor had been suggested in 1895, and was first developed by an English electrical engineer, Eric Laithwaite. Laithwaite discovered that it is possible to arrange two linear motors back-to-back, in order to produce a continuous oscillation without the use of any switching device. In 1946, the first large scale linear motor was built by Westinghouse Corporation, which was an aircraft launcher [10].

3.2 Basic principles of a linear motor

The Linear Motor is basically a rotating motor flatly opened. Instead of producing a rotating torque as in cylindrical machines, it produces a linear force. The speed is determined by the winding design and supply frequency. The stator is laid flat, without affecting the shape or the speed of the magnetic field. Hence, the flat stator produces a magnetic field that moves at constant speed [10].

Conceptually, all types of motors can have possible linear configuration (DC, induction, synchronous and reluctance). The DC motors and the synchronous motor require double excitation (field and armature). The DC linear motor can be grouped into moving-magnet, moving-armature and moving-coil motors. Linear induction motors can have various configurations: the air gap can be flat or cylindrical and the flux can be

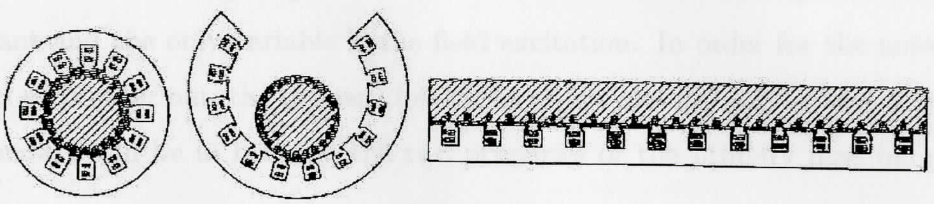

Figure 3-1: Imaginary process of unrolling a conventional motor to obtain a linear induction motor [10]

longitudinal or transverse.

In present-day automated machinery, there are a multitude of linear motion control applications. Whether a simple reciprocating single axis or a more complex rectilinear arrangement of multiple axes producing 2D or 3D motion, system designers have many choices when implementing the actuation of each individual linear axis of motion. Often, conventional rotary motors are chosen to drive some type of rotary–to–linear conversion mechanism, which is ultimately connected to the moving payload. A close examination would reveal that rotary–to–linear conversion mechanisms add inertia, friction, compliance, backlash, and wear, all of which compromise overall system performance. Linear motors, on the other hand, offer the system designer an elegant alternative in that they produce linear motion directly and, therefore, eliminate the need for conversion mechanisms such as leadscrews, belt drives, rack & pinions and con rod & crankshaft.

3.2.1 Forces produced

Linear electric machines develop two mutually perpendicular forces, one in the direction of motion (thrust) and the other, normal force perpendicular, to the direction of motion. The normal force may be an attraction force or a repulsion force between the primary and the secondary. A machine in which the net force is such that the secondary tends to be suspended over the primary, may be used mainly for suspension and is called the linear levitation machine. Conversely, a machine used primarily for producing thrust is called a linear motor. The thrust depends on both the armature and field excitations.

Therefore, for the moving-magnet linear motor, the armature field (permanent magnet) is constant and the only variable is the field excitation. In order for the normal forces to cancel each other out, the primary (stator in rotary motors) can be two, which means the secondary will be in between the two primaries or the primary may be cylindrical [8][21].

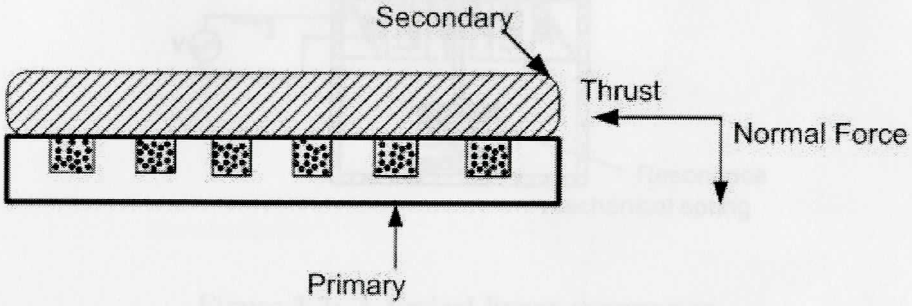

Figure 3-2: Single sided linear motor showing the direction of forces

3.3 Previous linear motor compressor

The conventional linear motor compressor consists of a linear motor coupled to a piston to a compression chamber. The other end of the linear motor is attached to a resonance mechanical spring, as shown in Figure 3-3. The disadvantage with this type of compressor is the shorter stroke length, which in order to obtain the adequate mass flow rate, has to be driven at high frequencies [30]. Therefore, this leads to more complex and expensive designs.

3.4 Application of a linear motor

Linear motors are increasingly popular solutions for current automation applications: actuators and robotics. Another interesting application of the linear motor application is in refrigeration application, such as Stirling Cooling, where a linear motor is used to drive a Free Piston Stirling Cooler and again on vapour compressor to drive a piston for

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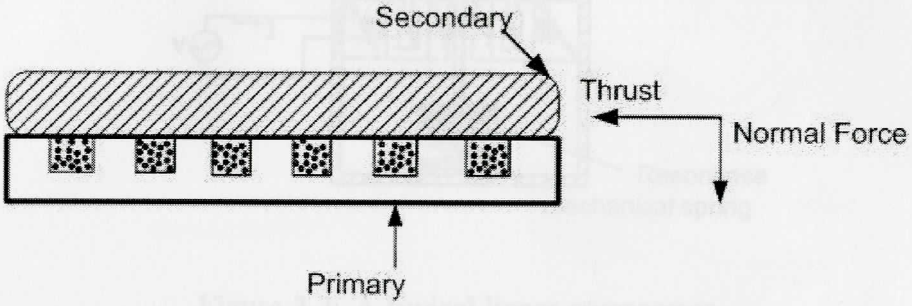

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3.4 Application of a linear motor

Linear motors are increasingly popular solutions for current automation applications: actuators and robotics. Another interesting application of the linear motor application is in refrigeration application, such as Stirling Cooling, where a linear motor is used to drive a Free Piston Stirling Cooler and again on vapour compressor to drive a piston for

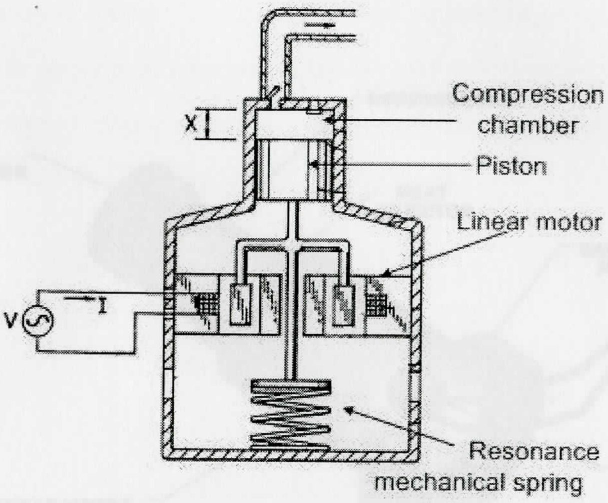


Figure 3-3: A typical linear compressor

compression, as shown in Figures 3-4 and 3-5.

3.5 Electromagnetic

The concept of Faraday's Law is that any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, the voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, and rotating the coil relative to the magnet.

The induced Voltage (Emf) is given by the Equation 3.1:

$$V = -N\frac{\Delta\phi}{\Delta t} \tag{3.1}$$

where

N is the number of turns;

$\phi = BA$ is the Magnetic flux;

B is the magnetic field; and

A is the area perpendicular to the magnetic field.

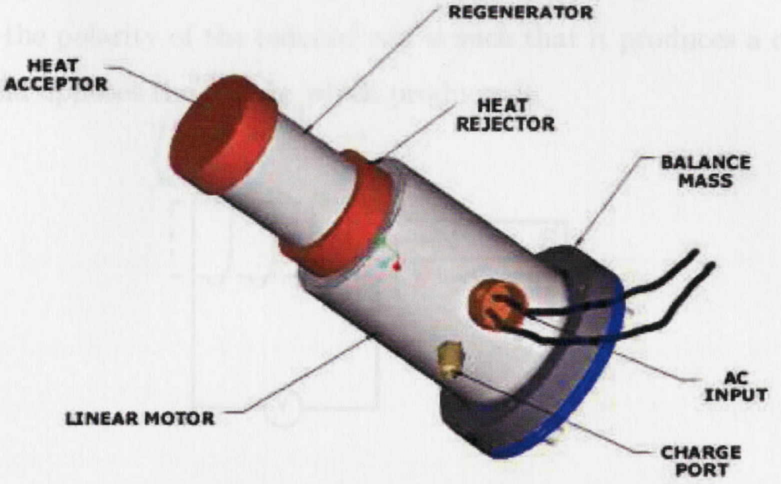


Figure 3-4: Free piston stirling cooler unit showing a linear motor [7]

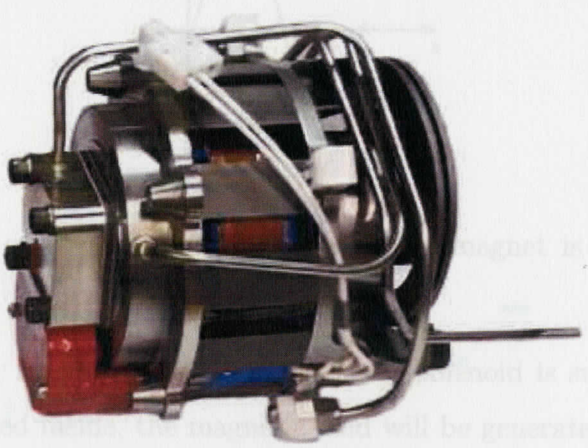


Figure 3-5: Linear compressor for domestic applications [6]

At a given rate of change of the flux through the coil, the voltage generated is proportional to the number of turns N which the flux penetrates. The minus sign (Lenz Law) means, that when an emf is generated by a change in magnetic flux, according to Faraday's Law, the polarity of the induced emf is such that it produces a current where the magnetic field opposes the change which produces it.

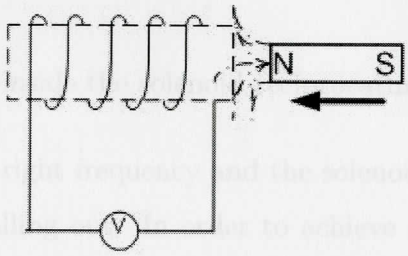


Figure 3-6: Emf induced in a solenoid when the magnet is pushed through

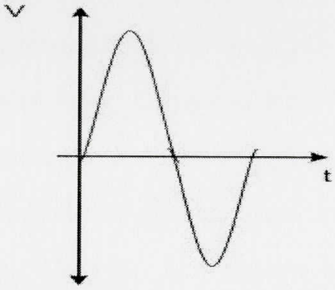


Figure 3-7: A typical emf waveform produced when a magnet is passed through the solenoid

From Equation 3.1, it can be deduced that if the solenoid is supplied with voltage and the magnet is placed inside, the magnetic field will be generated in a solenoid, and therefore, either repel or attract the magnet depending on the direction of current flowing and the orientation of the magnet, as shown in Figure 3-8.

Figure 3-8 shows the fundamental principles of a linear motor. By supplying an AC voltage to the solenoid, the reciprocating motion of the magnet will be achieved, provided

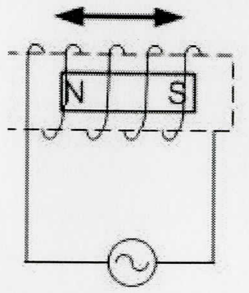


Figure 3-8: The magnet inside the solenoid reciprocating when the AC is applied

the magnet is driven at the right frequency and the solenoid is blocked on both sides to prevent the magnet from falling out. In order to achieve excessive driving forces, rare earth magnets (permanent magnets) were chosen.

Chapter 4

Rare earth magnets

4.1 History

Rare earth magnets are made from intermetallic compounds that include one or more rare earth elements. When the periodicity of elements was recognized, the periodic table of elements was created. Since there were spaces for elements which had not yet been discovered, they were called the rare earths. However, they are not rare and they are not earths. The missing elements were later discovered and were found to be metals [1].

Rare earth magnets, Neodymium Iron Boron (NdFeB) is a kind of magnetic material developed in the 1980's with excellent magnetic characteristics in terms of a high energy product, and high coercive force. They are also known as permanent magnets.

4.2 Applications of rare earth magnets

With excellent magnet characteristics, abundant raw material and relatively low cost, NdFeB magnets are under rapid development and wide application. They are replacing the traditional magnets of ferrite and AlNiCo. The applications include consumer electronics, computer peripherals, acoustics, magnetic resonance, biomedical and automation.

Depending on the particular application, the magnets can be selected according to their particular properties, as shown in Table 4.1.

Table 4.1: Characteristics of permanent magnets

Material	(BH)max ($MGOe$)	Hci (KOe)	Max. operating temperature (°C)	Coefficient of thermal expansion (/K)
Flexible Ceramic	≤2	≤3	100	——
Hard Ceramic	≤4	≤3	280	13
AlNiCo	≤10	≤2	550	11.4
NdFeB(Bonded)	≤10	≤10	125	60-80
NdFeB(Sintered)	≤45	≤30	180	3.4
SmCo(Bonded)	≤12	≤8	150	60.85
SmCo(Sintered)	≤30	≤25	250	9

From Table 4.1, it can be deduced that bonded magnets have a lower maximum energy product because the permanent magnetic materials are powered and mixed with plastic or rubber and is molded. Bonded magnets can be easily processed into any shape and can be formed into a single piece with other parts but since the proportion of magnetic material within the total volume is less, their magnetic force is reduced to the same degree.

Sintered magnets are a type of ceramic composed of the compressed powder of the alloy material being used. Sintering involves the compaction of fine alloy powder (magnetic material) in a die and then fusing the powder into a solid material. While the sintered magnets are solid, their physical properties are more similar to a ceramic and are easily broken and chipped.

4.3 The BH curve

The basis of magnet design is the BH curve, which characterizes each magnet material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field.

The second quadrant of the BH curve, commonly referred to as the “demagnetizing curve”, describes the conditions under which permanent magnets are used in practice. The three most important characteristics of the BH curve are the points at which it

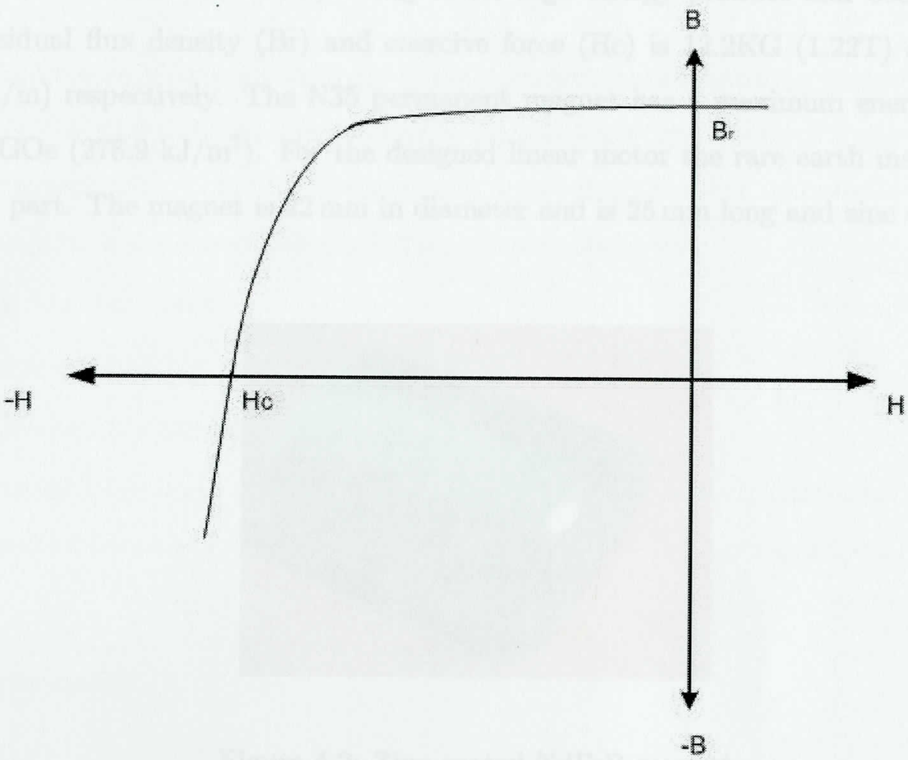


Figure 4-1: A typical second quadrant of the BH curve of a permanent magnet

intersects the B and H axes. The points at which the B and H are at maximum, is the Maximum Energy product of the magnet (BHmax).

Magnet Quality (BHmax): The quality of magnetic materials is best stated by the Maximum Energy Product (BHmax), measured in MegaGauss Oersted $MGOe$ or kilojoules per cubic metre kJ/m^3 (1 $MGOe$ =7.958 kJ/m^3). It is the maximum product of the flux density and field intensity along the magnet demagnetization curve. Even though this product has units of energy, it is not actual stored magnet energy, but a qualitative measure of a magnet's performance capability in a magnetic circuit [18] [1].

Residual flux density (Br) is the flux density, which corresponds to zero magnetizing force in a magnetic material after saturation in a closed circuit, while coercive force (Hc) is equal to the demagnetizing force required to reduce residual induction to zero in a magnetic field, after being magnetized to saturation.

For this thesis, the NdFeB grade N35 rare earth magnets were selected for the development of the linear motor, owing to its high energy product and coercive force. The residual flux density (Br) and coercive force (Hc) is 12.2KG (1.22T) and 12KOe (955kA/m) respectively. The N35 permanent magnet has a maximum energy product of 35MGOe (278.9 kJ/m^3). For the designed linear motor the rare earth magnet is the moving part. The magnet is 22 mm in diameter and is 25 mm long and zinc coated.

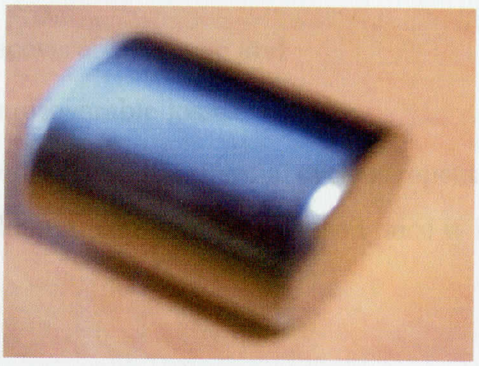


Figure 4-2: Zinc coated NdFeB magnet

4.4 Characteristics of rare earth magnet

There are two types of stabilities that are of prime interest in the application of magnets. Firstly, the magnets should retain their physical integrity when exposed to adverse operating conditions. Secondly, the magnetic properties of the magnet should remain constant after exposure to corrosive environments. It is well known that the magnetic properties of the magnets are harmfully affected when they are corroded, particularly, when the acidic environment is highly corrosive, and hence, the necessity to stabilise magnets in such environments [17].

There are a number of characteristics of rare earth magnets but for the purpose of this thesis, only characteristics that affect the implementation of these magnets, will be discussed.

4.4.1 Thermal stability

Thermal expansion of permanent magnets depend on the manufacturing process, whether it is bonded or sintered. Sintered magnets have a lower coefficient of expansion than bonded magnets [20]. This is the reason why sintered permanent magnets were chosen for this project. Temperature effects fall into three categories

- Reversible losses;
- Irreversible, but recoverable, losses; and
- Irreversible and unrecoverable losses.

Irreversible losses occur only once. If a thermal cycle is repeated, little or no additional loss is observed because a domain can only be reversed once it is magnetized [36].

Reversible losses

These are losses that are recovered when the magnet returns to its original temperature. Reversible losses cannot be eliminated by magnet stabilization and they are described by two temperature coefficients, namely α and β. Alpha is the reversible temperature coefficient of remanent flux density B_r and beta is the reversible temperature coefficient of coercive force H_{ci}, as defined in the following 4.1 and 4.2 equations, whilst T is the temperature.

$$\alpha = \left(\frac{1}{B_r}\right)\left(\frac{\Delta B_r}{\Delta T}\right) \times 100\% \tag{4.1}$$

$$\beta = \left(\frac{1}{H_{ci}}\right)\left(\frac{\Delta H_{ci}}{\Delta T}\right) \times 100\% \tag{4.2}$$

The temperature coefficient of H_{ci}, β, is generally much larger in magnitude than α, by as much as a factor of twenty. When the temperature of a magnetized magnet is changed from room temperature T_1 to a high temperature T_2, the fluctuation of the magnetic moment, due to thermal energy, changes the demagnetization curve, as in Figure 4-3. Accompanying this, the remanent flux density B_r and coercive force H_{cJ} decreases.

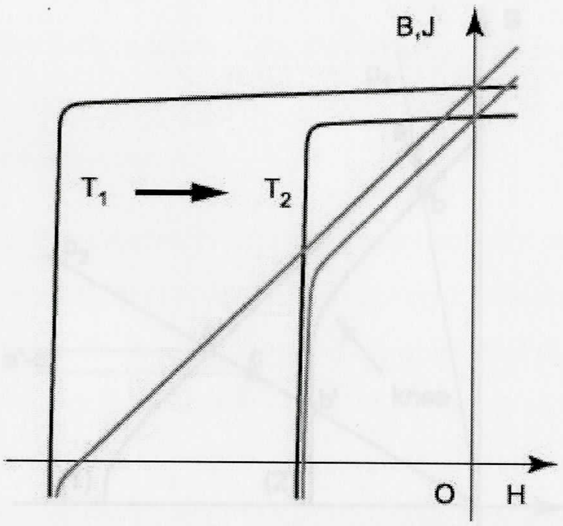


Figure 4-3: Demagnetization curve shifting because of thermal energy changes

Irreversible, but recoverable, losses

These losses are defined as partial demagnetization of the magnet because of exposure to high or low temperatures. These losses are only recoverable by remagnetization and are not recovered when the temperature returns to its original value. These losses occur when the operating point of the magnet falls below the "knee" of the demagnetization curve [4]. An efficient rare earth magnet design should have a magnetic circuit, in which the magnet operates at a permeance coefficient above the knee of the demagnetization curve at expected elevated temperatures. This will prevent performance variations at lifted temperatures.

The demagnetization curve in Figure 4-4 for a certain magnet at room temperature is (1) and the demagnetization curve for the same magnet at a higher temperature, is (2). If the usage permeance coefficient for that magnet is p1, then its working point is shifted temporarily from Point a to Point b by a higher temperature but is returned to Point a by cooling (reversible flux loss). However, if the usage permeance coefficient is p2, the working point, which had been at Point a, is shifted by higher temperatures to Point b, which is below the knee of the curve. In this case, the working point that has shifted, does not return to its original Point a even when the magnet is cooled, but rather only

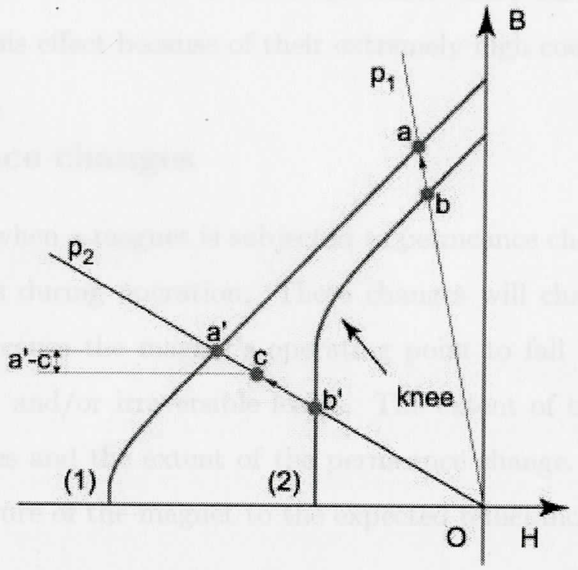


Figure 4-4: Irreversible losses shown by demagnetization curve [4]

recovers to Point c. The resulting flux loss a-c is called the initial flux loss. The degree of this initial flux loss, the same as for reversible the flux loss, is determined by the type of rare earth magnet, the usage temperature, and the usage permeance coefficient.

Irreversible and unrecoverable losses

Metallurgical changes occur in magnets that are exposed to high temperatures and are not recoverable by remagnetization. Partially demagnetizing a magnet by exposure to elevated temperatures in a controlled manner, stabilizes the magnet with respect to temperature. The slight reduction in flux density improves magnetic stability because domains with low commitment to orientation, are the first to lose the orientation [5].

4.4.2 Time

The effect of time on modern, permanent magnets is minimal. Studies have shown that permanent magnets will see changes immediately after magnetization. These changes, known as "magnetic creep", occur as less stable domains are affected by fluctuations in thermal or magnetic energy, even in a thermally stable environment. This variation is reduced as the number of unstable domains decrease. Rare earth magnets are not as likely to experience this effect because of their extremely high coercivities.

4.4.3 Reluctance changes

These changes occur when a magnet is subjected to permeance changes, such as changes in air gap dimensions during operation. These changes will change the reluctance of the circuit, and may cause the magnet's operating point to fall below the knee of the curve, causing partial and/or irreversible losses. The extent of these losses depend on the material properties and the extent of the permeance change. Stabilization may be achieved by pre-exposure of the magnet to the expected reluctance changes.

4.4.4 Shock, stress and vibration

Below destructive limits, these effects are minor on modern magnet materials. However, rigid magnet materials are brittle in nature, and can easily be damaged or chipped by improper handling. Samarium Cobalt, in particular, is a fragile material and special handling precautions should be taken to avoid damage. Thermal shock when Ceramics and Samarium Cobalt magnets are exposed to high temperature gradients, can cause fractures within the material and should be avoided.

4.4.5 Coating

Neodymium Iron Boron magnets are susceptible to corrosion and consideration should be given to the operating environment to determine if coating is necessary. Nickel or tin plating may be used for Neodymium Iron Boron magnets, however, the material should be properly prepared and the plating process properly controlled so that successful plating can occur. Plating houses experienced in the plating of NdFeB materials are difficult to locate, and must be furnished with the necessary information for proper preparation and control of the process. Aluminum chromate or cadmium chromate vacuum deposition has been successfully tested, with coating thickness as low as 12.7 μm. Teflon and other organic coatings are relatively inexpensive and have also been successfully tested [5]. A further option for critical applications is to apply two types of protective coatings or to encase the magnet in stainless steel or other housing, to reduce the chances of corrosion.

4.5 Magnetization

Permanent magnet materials are believed to be composed of small regions or "domains", each of which exhibit a net magnetic moment. An unmagnetized magnet will possess domains that are randomly oriented with respect to each other, providing a net magnetic moment of zero [5]. Thus, a magnet, when demagnetized, is only demagnetized from the observer's point of view. Magnetizing fields serve to align randomly oriented domains to give a net, externally observable field.

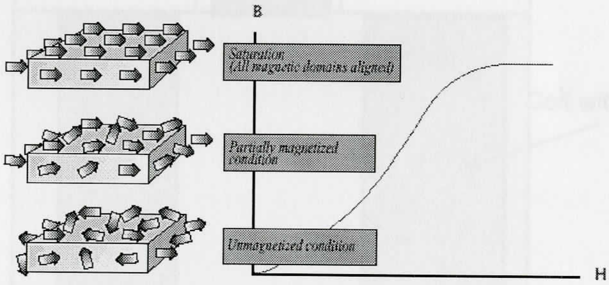


Figure 4-5: Different stages of the magnetization process

The objective of magnetization is initially to magnetize a magnet to saturation, even if it will later be slightly demagnetized for stabilization purposes. Saturating the magnet and then demagnetizing it in a controlled manner, ensures that the domains with the least commitment to orientation will be the first to lose their orientation, thereby leading to a more stable magnet. Not achieving saturation, on the other hand, leads to orientation of only the most weakly committed domains, hence leading to a less stable magnet.

4.5.1 Two common types of magnetization

The two common types of the magnetization process are the DC and capacitor discharge magnetizers.

DC magnetizers

DC magnetizers employ large coils through which a current is applied for a short duration by closing a switch. The current flowing through the coil produces a magnetic field, which is usually directed by the use of iron cores and pole pieces, with magnets placed in the gap between the pole pieces. DC magnetizers are only practical for magnetizing Alnico materials, which have a low magnetizing force requirement, or small sections of Ceramic materials.

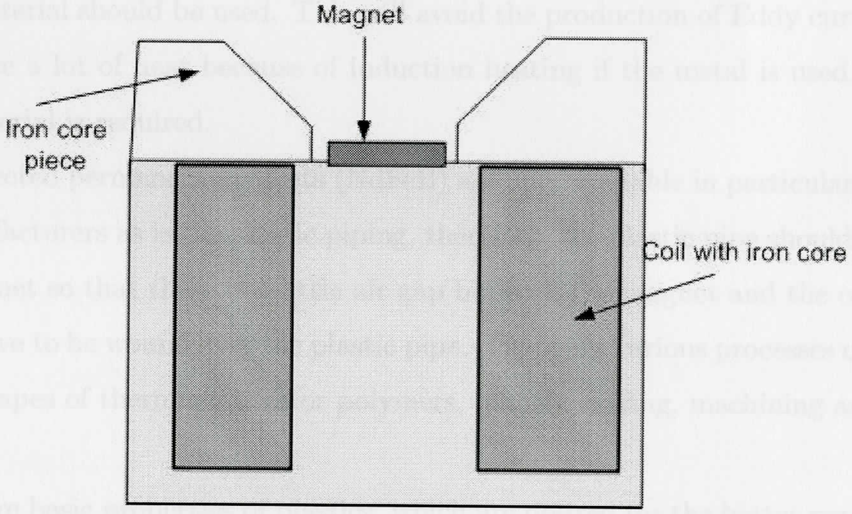


Figure 4-6: DC Magnetizer

Capacitor discharge magnetizers

Capacitor discharge magnetizers employ capacitor banks that are charged and then discharged through a coil. Extremely high magnetizing fields (in the range of 100 KOe) can be achieved by using special coils and power supplies.

Chapter 5

Plastic technology

In order for the two magnetic fields of the coils and rare earth magnet to interact properly to work as a linear motor and produce the reciprocating motion, non electrically conducting material should be used. This will avoid the production of Eddy currents, which will produce a lot of heat because of induction heating if the metal is used. Therefore, plastic material is required.

The selected permanent magnets (NdFeB) are only available in particular dimensions from manufacturers as is the plastic piping, therefore, the plastic pipe should be made to fit the magnet so that there is a little air gap between the magnet and the coils because the coils have to be wound over the plastic pipe. There are various processes of producing different shapes of thermoplastics or polymers, namely casting, machining and injection moulding.

There are basic properties of plastics, which are desired for the better performance of the linear compressor:

- Low coefficient of friction to reduce wear;
- High tensile strength to withstand compression;
- Low coefficient of thermal expansion;
- High temperature resistance; and
- Resistance to mineral oils and solvents (resistance to refrigerants).

5.1 Plastic machining

5.1.1 Acetal

After looking at most of the available plastic materials with the desired properties and affordability, the acetal plastic was chosen. Acetals have a unique balance of physics properties not available with metals and most other plastics. Acetals absorb a minimal amount of moisture and their physical properties remain constant in a variety of environments. Low moisture absorption provides excellent dimensional stability for close-tolerance machined parts. Acetals are produced from copolymer and homopolymer resins, which provide a high modulus of elasticity coupled with strength, stiffness and toughness. They are also characterized by a low coefficient of friction and have good bearing characteristics [27].

Typical properties

- Easily machined;
- Good abrasion resistance;
- Excellent dimensional stability;
- High natural lubricity;
- High mechanical strength;
- High rigidity; and
- Low moisture absorption.

5.1.2 Advantages of plastic machining

Plastic machining offers several distinct advantages over moulding for low volume production, which include:

- Zero up-front tooling costs;

- Drastically reduced lead-times;
- Close tolerances;
- Plastic machining is perfect for R&D and prototypes; and
- Part design can be altered cost effectively.

5.2 Plastic casting

Casting is a process by which a material is introduced into a mould while it is liquid, allowed to solidify in the shape inside the mould, and then removed producing a fabricated object, part, or casing. Casting is often used for creating one or more copies of an original piece of three-dimensional artwork. It is also used extensively in the automobile manufacturing industry, such as the casting of engine blocks or cylinder heads.

5.2.1 Vacuum casting

Amongst different types of plastic casting, vacuum casting was preferred because of its advantages towards the desired design. Similar to traditional casting processes, the vacuum casting process involves the pouring of a liquid (typically a polyurethane plastic), into a moulded form that is pieced together along a parting line. There are several unique aspects and advantages to the vacuum casting process that make it ideal for use in rapid prototyping. The process is made up of three production steps: mould making, part pouring, and the curing process, which includes the post cure finishing.

The primary advantage of the vacuum casting process is its low cost. Compared with traditional, working, prototyping development processes, a vacuum cast urethane part is less expensive with a quicker turn around and reworking flexibility. Silicone rubber moulds produce excellent reproductions of patterned details, while allowing for easy demoulding of especially complex pieces.

Vacuum cast moulds are made of various grades of silicone rubber. The rubber encloses a form that is cast from a pattern. Patterns can be production parts. Silicone rubber moulds generally contain several similar features. The pattern (pre-casting) is taped, gated, vented and suspended. The tape is placed on the pattern typically along a continuous edge or surface. The pattern is taped to allow for repeated separation of the mould and clean parts with no apparent "witness" line. The pattern is also connected to a sprue and gate arrangement that allows the liquid urethane mixture to fill the cast form completely and efficiently. As parts are poured into the mould, liquid plastic displaces air in the form cavity to fill the part. Moulded patterns are vented to allow for the complete displacement of bubbles and the indication of a complete filling of the mould. Once venting is completed, the pattern is suspended in an appropriately-sized mould box.

As with the urethane plastics, the mould rubber is a two-part resin/hardener mixture. The vacuumed mixture is then poured, filling the mould box around the pattern. Once cured, the rubber sections of the mould can be cut away from the pattern and the mould used to pour pieces.

To produce a casting, a two-part polyurethane mixture is poured into the mould cavity under vacuum. On the average, one silicone rubber mould can produce about 25 urethane pieces, varying slightly, depending on the geometry of the pattern. The vacuum, created by the casting machine's pump, eliminates air from both the liquid plastic and the mould cavity. Once fully combined, the mixture is carried from a material chamber to a mould chamber through tubing by gravity. Mixing time, mixing speed and temperature of the polyurethane, are all factors in the cure time and shrink rate of the cure part.

Fastcast polyurethane

Polyurethane was used for casting the motor enclosure. It has a low coefficient of friction, resistant to organic solvents and it can withstand higher temperatures. It is available in two liquid mixtures (Type A and B), which are mixed in a one-to-one ratio when casting. Type A is polyol and type B is isocyanate. Casting was found to be an ideal process because of its low cost and the whole coils of the linear motor can be embedded in plastic.

Casting Procedure

During the casting process, there were two major goals: firstly, to cast the sleeve together with the coils inserted and, secondly, to place the coils as close as possible to the inner diameter (i.e. closer to the magnet), in order to reduce an air gap.

- Step 1: The coils are lightly wound around the 22.00 mm diameter and 80 mm long mild steel rod. The rod's diameter is 0.25 mm bigger than the permanent magnet. Ideally the rod should be the same as the permanent magnet but because polyurethane contracts when it sets, the 0.25 mm would allow for shrinkage.

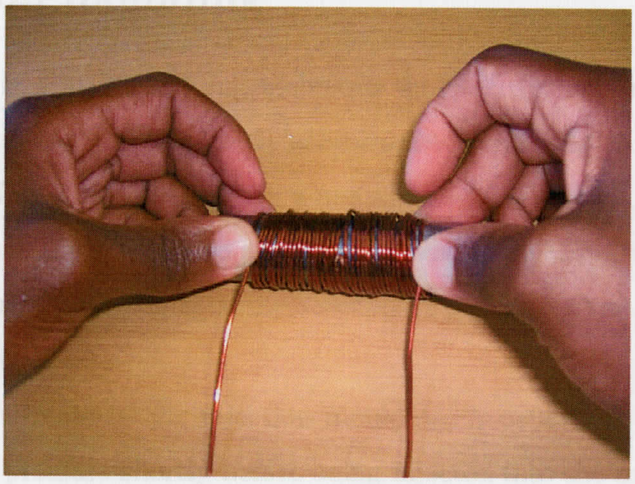


Figure 5-1: Coils wound around the rod, ready to be placed inside the silicone mould for casting

- Step 2: The rod, with coils, is placed upright inside the silicone mould. The two part silicone mould is joined and taped together with the rod and coils inside the silicone mould and then placed inside the vacuum chamber.
- Step 3: The two mixtures are measured and stirred separately inside the vacuum chamber to remove air bubbles, then the two mixtures are mixed and poured inside the vacuum chamber by the mechanism. The part will cure after 20 minutes.
- Step 4: Finally, the two silicone mould parts will be separated and the product removed. The rod will be removed leaving a tubular cylinder with coils embedded inside, as shown in Figures 5-2 and ??.

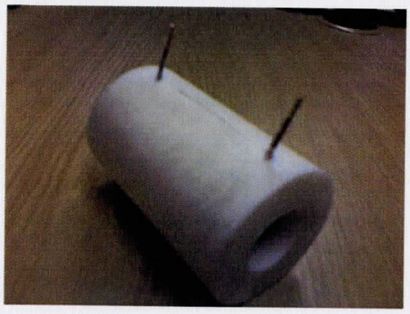


Figure 5-2: The end product after vacuum casting

5.3 Injection moulding

Injection moulding is a manufacturing technique for making parts made of plastic material. Molten plastic is injected at high pressure into a mould, which is the inverse of the desired shape. The mould is made by a mouldmaker from metal, usually either steel or aluminum, and precision-machined to form the features of the desired part. Injection moulding is widely used for manufacturing a variety of parts from the smallest component to entire body panels of cars.

The resin, or raw material for injection moulding, is usually in pellet form, and is melted by heat and pressure shortly before being injected into the mould. The channels through which the plastic flows toward the chamber will also solidify, forming an attached frame. The quality of the moulded part depends on the quality of the mould, the care taken during the moulding process, and upon details of the design of the part itself. It is essential that the molten resin be at just the right pressure and temperature, so that it flows easily to all parts of the mould.

Moulds are very expensive to manufacture, therefore, they are usually only used in mass production when thousands of parts are produced. Moulds are typically constructed from hardened steel or aluminum. The choice of material used to build a mould is primarily one of economics. Steel moulds generally cost more to construct but their longer lifespan will offset the high initial cost over the higher number of parts made in the mould before it wears out.

Chapter 6

Design implementation

6.1 Design background

The initial approach to the project was to develop a compressor that will be able to draw air from an atmosphere and compress it. Future work will include designing a linear compressor for vapour compression.

6.2 Design considerations

The proposed linear motor compressor is planned to be cost effective by designing the motor with as little components and materials as possible. Therefore, one of the advantages is that the permanent magnet is used as a secondary (rotor for rotary motor) for the linear motor and the magnet itself, being solid cylindrical, is used as free piston, which is the only moving part.

6.2.1 Permanent magnet

The permanent magnet has a maximum energy product greater than 45 $MGOe$ (360 kJ/m^3), which is the maximum energy that a permanent magnet can supply to an external magnetic circuit when operating in demagnetization. The larger the BHmax, the more energy a permanent magnet can convert in the energy conversion process as a reversible medium, while it is still in a stabilized condition.

6.2.2 Airgap

An airgap plays an important role in magnetic circuits because even the elementary physics state that the magnetic field of a magnetic dipole, is approximately proportional to the inverse **cube** of the distance from the dipole. Therefore, if the distance from the magnet is doubled, the magnetic field strength will be reduced (roughly) by a factor of 8 [3]. As a result, when designing a linear compressor, an airgap should be kept to a minimum in order to produce more force.

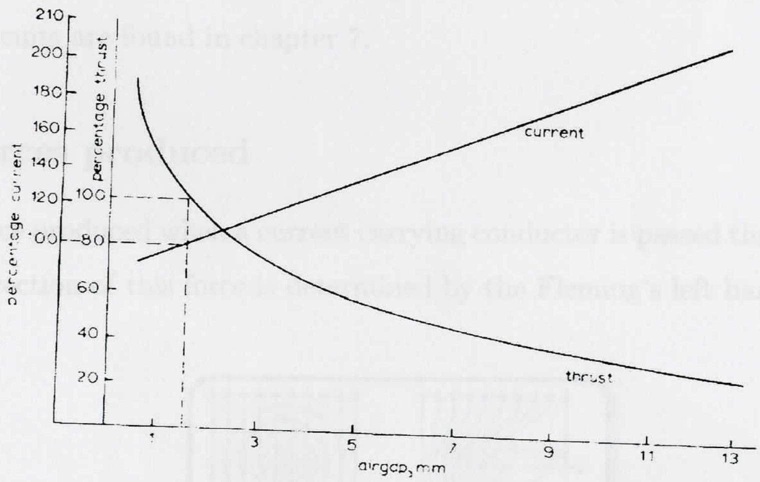


Figure 6-1: Effect of airgap on thrust and line current [21]

6.2.3 Driving coils

The driving coils will provide the external magnetic circuit to the permanent magnet in a linear compressor. This external magnetic circuit can supply enough force to compress air in a compression chamber of the linear compressor to the desired pressure.

6.2.4 Plastic enclosure

As mentioned earlier, there are different types of processes involved in developing a plastic enclosure particular care was taken in selecting the process and type of plastic material to be used for the linear compressor. The plastic materials were chosen with regard to the desired properties of the plastic material to work in a compressor environment, as the primary objective of this thesis is to develop a low cost product, when selecting, cost was also taken into consideration.

6.2.5 Driving circuitry

The criteria used when selecting electronic components was to source low cost components and surface-mount components to keep a minimum size of the printed circuit board. In this way, the entire compressor physical magnitude will be kept small and compact. More details on circuits are found in chapter 7.

6.2.6 Forces produced

There is a force produced when a current carrying conductor is passed through a magnetic field. The direction of this force is determined by the Fleming's left hand rule.

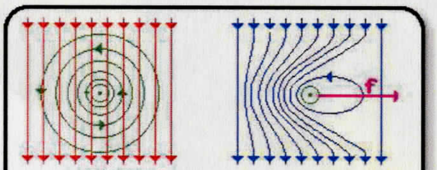


Figure 6-2: Force on the conductor shown when passed through the field

$$F = Bil$$

where

F is force on current carrying conductor;

i is current in a conductor; and

l is the length of the wire.

The force mentioned above is the force on the conductors, therefore, the actual force that will cause the permanent magnet to move will result in an opposite direction because of Newton's third law. It states that for every action, there is an equal and opposite reaction.

6.3 First prototype

Acetal plastic was used for the first prototype. The machined acetal enclosure comprises of two slots for the coils and a precision drilled hole in the middle. The cavity (hole) is used as a cylinder for the piston (permanent magnet), as shown in Figure 6-3.

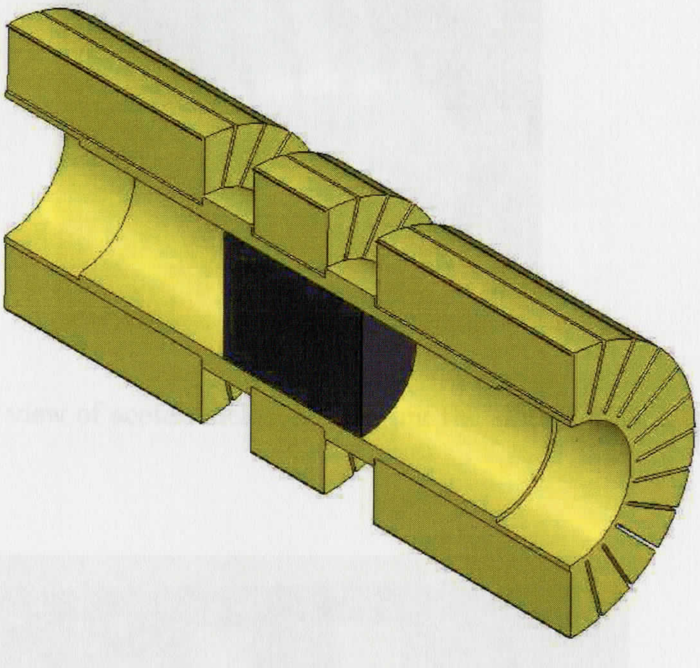


Figure 6-3: Sectional drawing of the machined acetal material for the compressor at 1:1 scale

6.3.1 Coils winding

The two driving coils were wound onto the slots of the acetal casing, using a coil winding machine. These coils were connected in a parallel opposing manner.

6.3.2 Laminations

In order to strengthen the magnetic path, the laminations that are 0.5 mm thick were slotted along the enclosure. This ensures that the flux around the coils and the permanent magnet is contained.

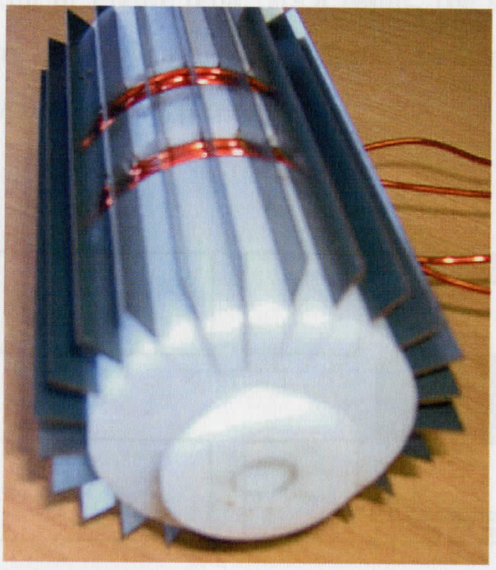


Figure 6-4: Side view of acetal enclosure showing the slotted steel laminations

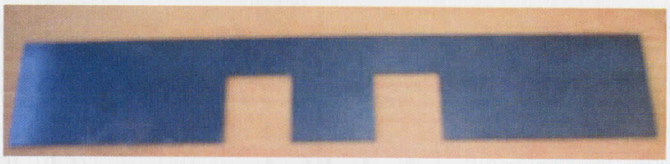


Figure 6-5: Laminations used for containing flux path

6.3.3 Valve housing inserts

When the piston reciprocates inside the cylinder in a sealing manner so that compression may occur, end pieces should be bonded on both ends of the cavity. These end pieces should incorporate inlet and outlet valves on both ends. Different types of valves were explored and the suitable valve type chosen were the pressure dependant valves because they can be cost-effectively produced.

6.3.4 Problems

The problems encountered with the first prototype was that the moving magnet tends to get stuck between the coil in Figure 6-6a. As a result, the solution was to design a coil in such a way that there is always a maximum force produced at any position of the magnet, as shown in the second prototype.

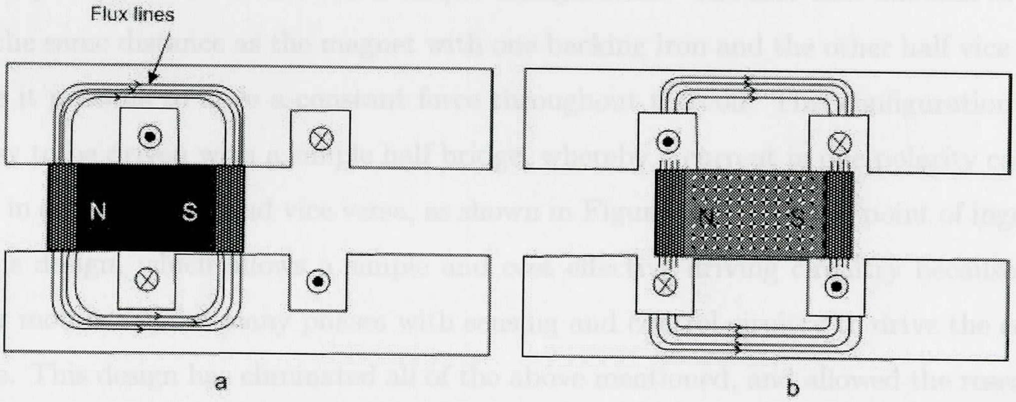


Figure 6-6: a) Permanent magnet got stuck between the coil, .i.e. no force; b) maximum force being produced

6.4 Second prototype

There were a few difficulties encountered with the first prototype, namely:

- Since long strokes were desired for better performance, as a result, the coils' structure did not work properly in the sense that the permanent magnet tended to get stuck on either side of the chamber where the exciting field flux cannot reach the permanent magnet.

- The acetal material was machined, therefore, the airgap could not be reduced further, as desired, because the coil slots cannot be machined down to under a two millimetre thickness, otherwise the acetal would break.

The plastic manufacturing process that was suitable for the desired coils' structure was the vacuum casting.

6.4.1 Improved coil structure

The improved coil structure was a simple configuration. The fact that one half of a coil was the same distance as the magnet with one backing iron and the other half vice versa, made it possible to have a constant force throughout the coil. This configuration made it easy to be driven with a simple half bridge, whereby a current in one polarity causes a force in one direction, and vice versa, as shown in Figure 6-7. This is a point of ingenuity in this design, which allows a simple and cost effective driving circuitry because most linear motors require many phases with sensing and control ciruitry to drive the coils in phase. This design has eliminated all of the above mentioned, and allowed the researcher to build a simple and cost effective drive circuitry.

6.4.2 Maximizing the stroke length

Maximum stroke length is of the utmost importance because higher volumetric efficiency can be reached. This means that there will be less residual volume during the gas discharge stage. The maximum stroke length is achieved by making the length of one driving coil the same distance as the permanent magnet (piston), plus one backing iron, as shown in Figure 6-8. The maximum stroke length was found to be 25 mm.

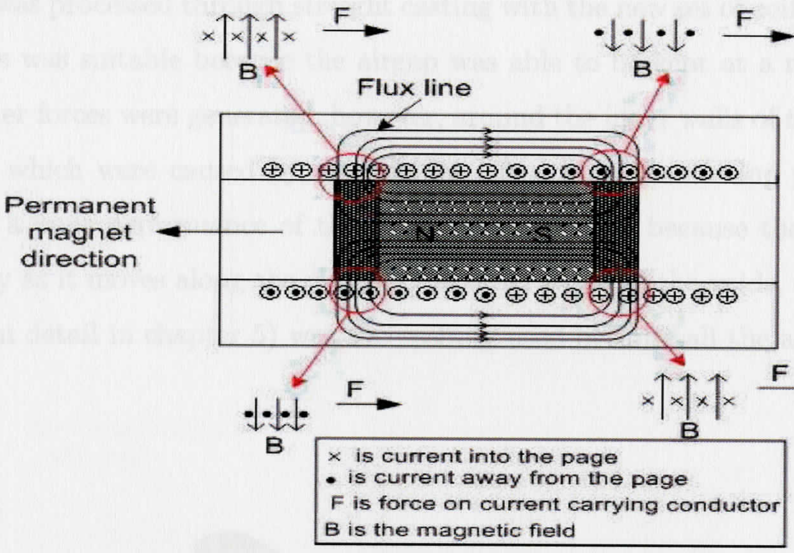


Figure 6-7: Force generated at the pole face of the permanent magnet

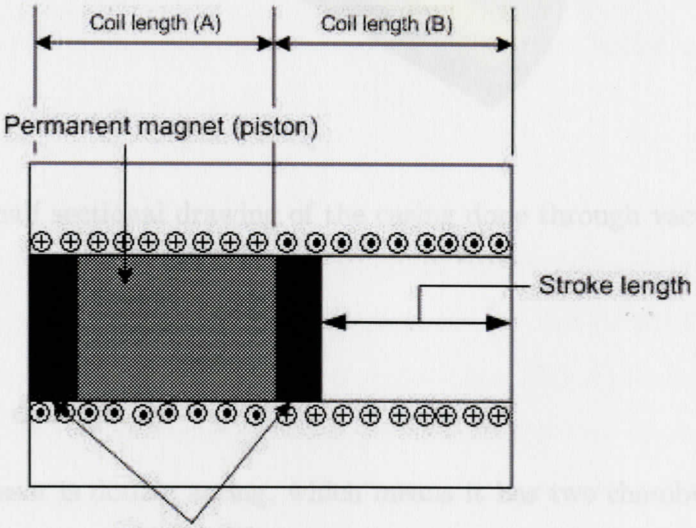


Figure 6-8: Maximum stroke length

6.4.3 Vacuum casting

The casing was processed through straight casting with the new set of coils configuration. This process was suitable because the airgap was able to be kept at a minimum which means greater forces were generated, however, around the inner walls of the cavity, there were voids, which were caused by air bubbles left during the casting process. These voids cause a poor performance of the compression process because the piston cannot seal properly as it moves along the cylinder. In order to avoid the voids, vacuum casting (explained in detail in chapter 5) was successfully used because all the air bubbles were removed.

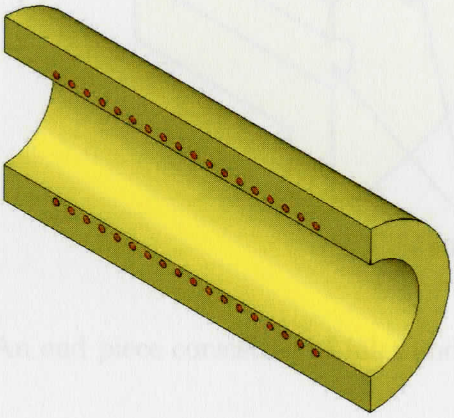


Figure 6-9: The half sectional drawing of the casing done through vacuum casting with coils embedded

6.4.4 Valve design

Since the compressor is double acting, which means it has two chambers, it compresses air on one chamber while drawing air in on the other chamber, and the opposite happens in the next half cycle. Initially, the valves were made of machined acetal material but due to the limited space and complexity of the machining needed on the piece, it was difficult to do. As a result, brass was the second option because it is not magnetic. The brass will not become heated due to induction heating as the brass pieces are situated outside the solenoid, (i.e. on both sides of the casing).

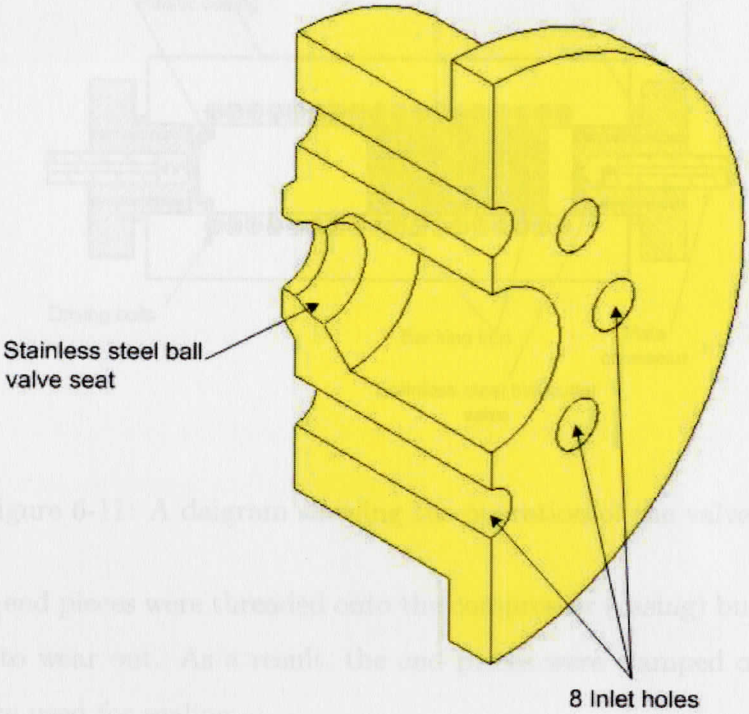


Figure 6-10: An end piece consisting of inlet and outlet valves

Operation

The operation discussed here relates on valves on one half of the linear compressor because in terms of valves functioning, whatever happens on one side of the linear compressor, the opposite occurs on the other side. The outlet pipes (high pressure pipes) on both sides of the compressor are connected through male connectors to the compressor and these outlet pipes are joined together to form one high pressure outlet pipe. The inlet valve consists of a silicone flap, while the outlet valve comprises of a stainless steel ball, as shown in Figure 6-11. When the permanent magnet moves towards the end piece (compressing), the silicone flap (suction valve) closes the 8 inlet holes while the stainless steel ball discharge valve is still in a closed position until the pressure inside the chamber is more than the pressure inside the outlet pipe.

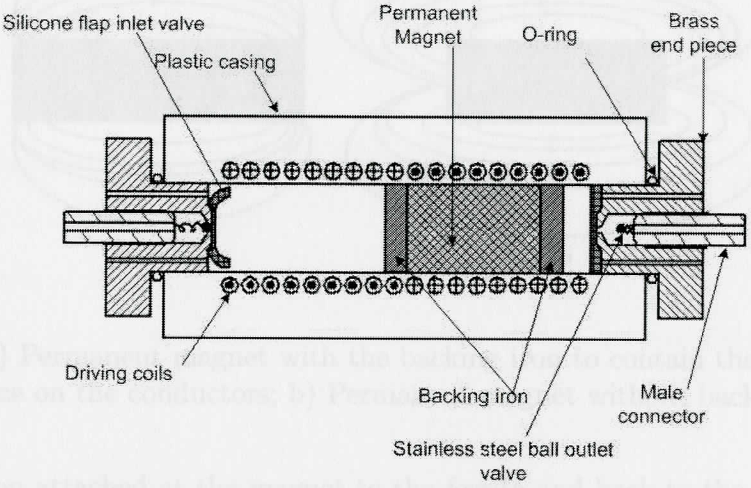


Figure 6-11: A daigram showing the operation of the valves

Initially, the end pieces were threaded onto the compressor (casing) but gradually, the threads tended to wear out. As a result, the end pieces were clamped onto the casing. The O-rings were used for sealing.

6.4.5 Backing iron

In order to contain the flux path of the permanent magnet, backing iron discs were attached at each end of the magnet. These backing iron discs have the same diameter as the permanent magnet but are 5 mm thick. This thickness was determined empirically by measuring what thickness of mild steel is required to completely contain all the flux in a semi closed loop. The 0.5 mm mild steel laminations were added gradually on top of the permanent magnet's pole until there was no residual magnetic field left.

6.4.6 Magnetic materials

In future work, in order to contain the flux in a closed loop of least reluctance, the ferrite or iron powder will be bonded with the thermoplastics during the vacuum casting of the casing. As a result, the flux path from the permanent magnet will be contained from

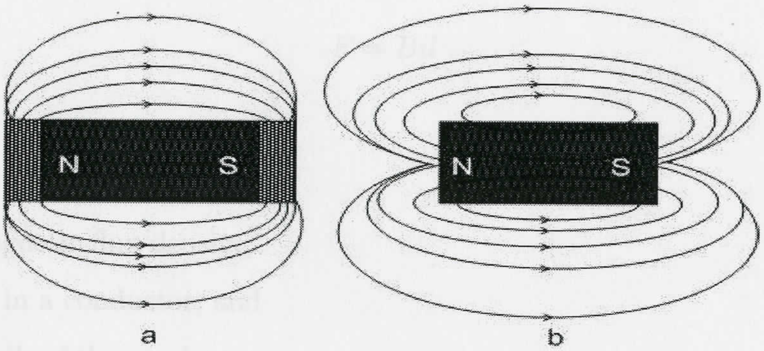


Figure 6-12: a) Permanent magnet with the backing iron to contain the flux in order to exert more force on the conductors; b) Permanent magnet without backing iron

the backing iron attached at the magnet to the ferrite and back to the magnet through another backing iron, as shown in Figure 6-13.

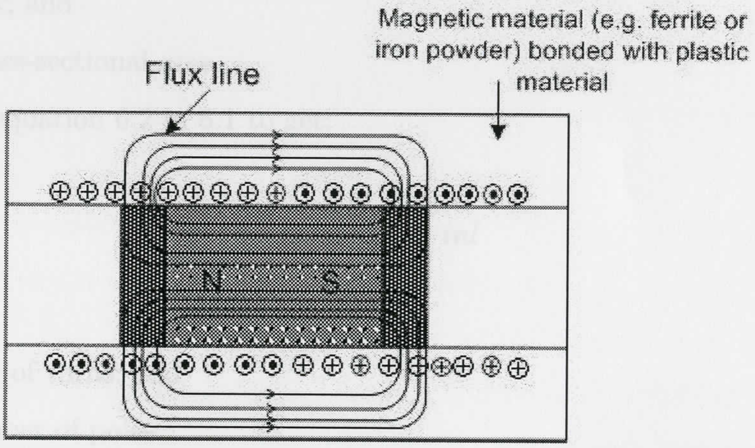


Figure 6-13: Flux contained in a closed loop

6.5 Permanent magnet calculations

6.5.1 Force

The calculation of force produced in a current carrying conductor:

$$F = Bil \tag{6.1}$$

where

B is the magnetic flux density;

i is current in a conductor; and

l is the length of the conductor.

B is unknown, therefore, to calculate the magnetic field from the backing iron attached to the magnets:

$$B = \frac{\phi}{A} \tag{6.2}$$

where

ϕ is the flux; and

A is the cross-sectional area.

Substitute equation 6.2 in 6.1 to get:

$$F = 2\left(\frac{\phi}{A}\right) inl \tag{6.3}$$

where

n is number of turns; and

2 is for number of poles.

Area is calculated as follows:

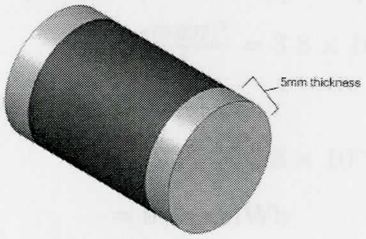


Figure 6-14: The permanent magnet with the backing irons

$$A = \pi d \times thickness$$

$$A = \pi \times 0.022 \times .005$$

$$= 3.46 \times 10^{-4}\,\mathrm{m}^2$$

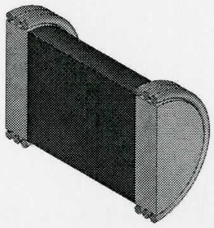


Figure 6-15: A cut sectional-drawing of a magnet with the interacting wires, which produces external flux

n is approximately 3 turns over a pole and l is the circumference (πd), which is 0.069 m.

The current is assumed to be 1 A;

The only unknown in equation 6.3 besides force, is ϕ.

The magnetic flux density of the type of permanent magnet used on this design is 1.22 T from its data sheet. This flux density may not be used in the calculations because the flux exits on the magnet from the sides of the backing iron, and not on the face of the magnet.

The area (surface area on a pole face) of this type of permanent magnet is:

$$A = \frac{\pi(0.022)^2}{4} = 3.8 \times 10^{-4}\,\mathrm{m}^2$$

Therefore, the resultant flux is:

$$\phi = 1.22\,\mathrm{T} \times 3.8 \times 10^{-4}\,\mathrm{m}^2$$

$$= 0.464\,\mathrm{mWb}$$

Since the backing irons are attached to the magnet, the resultant flux density is calculated as:

$$B = \frac{0.464\,\mathrm{mWb}}{3.46\times10^{-4}\,\mathrm{m}^2}$$

$$= 1.34\,\mathrm{T}$$

Note: area used is for the backing iron because that is where the flux exits the magnet.

$$F = 2 \times 1.34\,\mathrm{T} \times 1\,\mathrm{A} \times 3 \times 0.069\,\mathrm{m}$$

$$= 0.55\,\mathrm{N}$$

Chapter 7

Circuit design

The complete circuitry system designed to drive a linear compressor consists of various circuits. The system comprises of a micro controller for driving signals and the feedback, driving circuit.

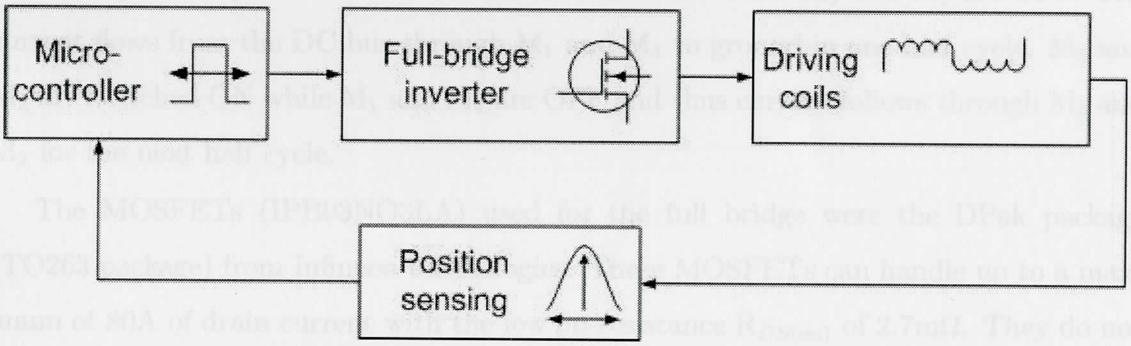


Figure 7-1: A block diagram of the complete permanent magnet piston compressor system

7.1 Full-bridge inverter

The full-bridge inverter was chosen over the half-bridge inverter mainly because the linear motor is driven at a low frequency. Therefore, the matching capacitors' value needed if it was driven by the half-bridge inverter, will be big in value, physical size and cost.

The full-bridge inverter comprises of four semiconductor switches known as MOS-

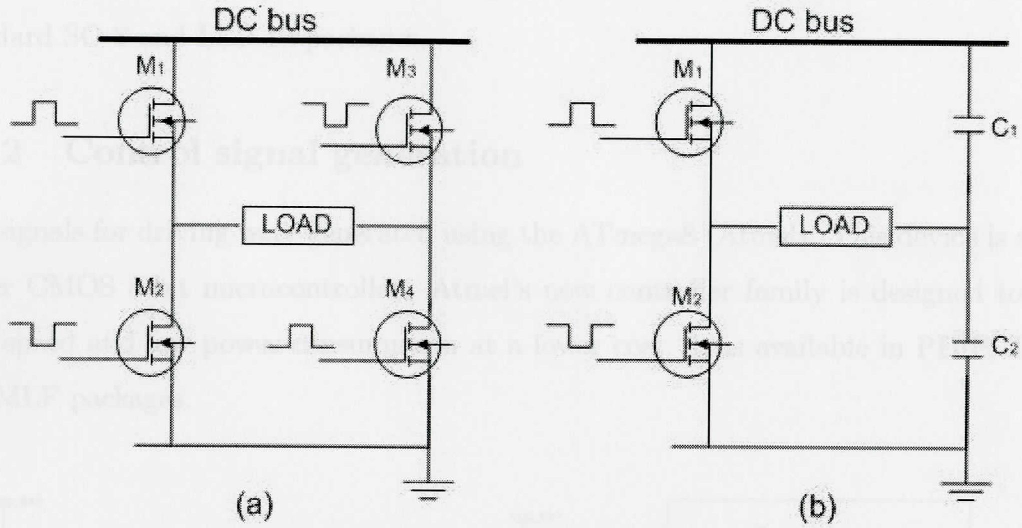


Figure 7-2: a) Full-bridge inverter; b) Half-bridge inverter with C_1 and C_2as the matching capacitors

FETs. M_1 and M_4 are switched ON at the same time while M_3 and M_2 are OFF. The current flows from the DC bus through M_1 and M_4 to ground in one half cycle. M_3 and M_2 are switched ON while M_1 and M_4 are OFF and thus current follows through M_3 and M_2 for the next half cycle.

The MOSFETs (IPB03NO3LA) used for the full bridge were the DPak package (TO263 package) from Infineon technologies. These MOSFETs can handle up to a maximum of 80A of drain current with the low on-resistance $R_{DS(on)}$ of 2.7mΩ. They do not need a heatsink to deliver the high current as they only need a $6\,\mathrm{cm}^2$ pad size on a PCB. The above mentioned advantages make this device an obvious choice because the size of the PCB is kept to a minimum.

The drain to source voltage is 25V, which is within the specifications of the circuit. In this linear motor, the current is directly proportional to the force produced.

7.1.1 MOSFET drivers

LM5100 is the MOSFET driver selected. It drives both the high and low side of the N-channel MOSFET and it has independent high and low driver logic inputs. Its logic input makes it compatible to be controlled using a microcontroller. This device is available in standard SO-8 and LLP-10 packages.

7.1.2 Control signal generation

The signals for driving were generated using the ATmega8 (Atmel). This device is a low-power CMOS 8-bit microcontroller. Atmel's new controller family is designed to offer high speed and low power consumption at a lower cost. It is available in PDIP, TQFP and MLF packages.

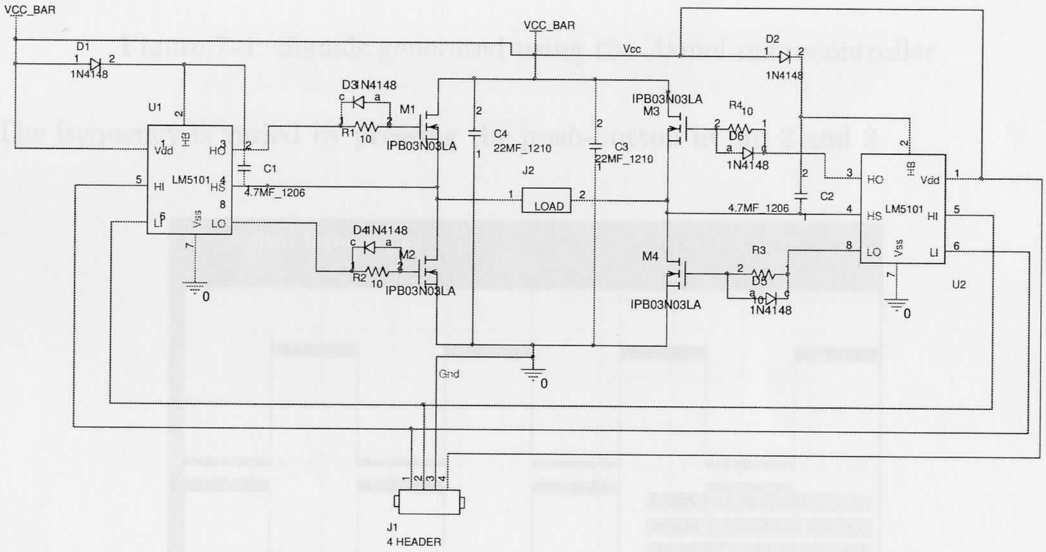


Figure 7-3: Circuit diagram for driving the permanent magnet piston compressor

7.2 Linear motor driven on open-loop mode

Initially, the linear motor was driven on open-loop, which means no feedback for position control. The 50% duty cycle signals were generated using the microcontroller with a fixed deadtime of 4 ms. A deadtime is a time when the two driving signals are off at the same time to avoid the MOSFETs from switching on at the same time and, thus, MOSFETs may not be blown, as shown in Figure 7-6.

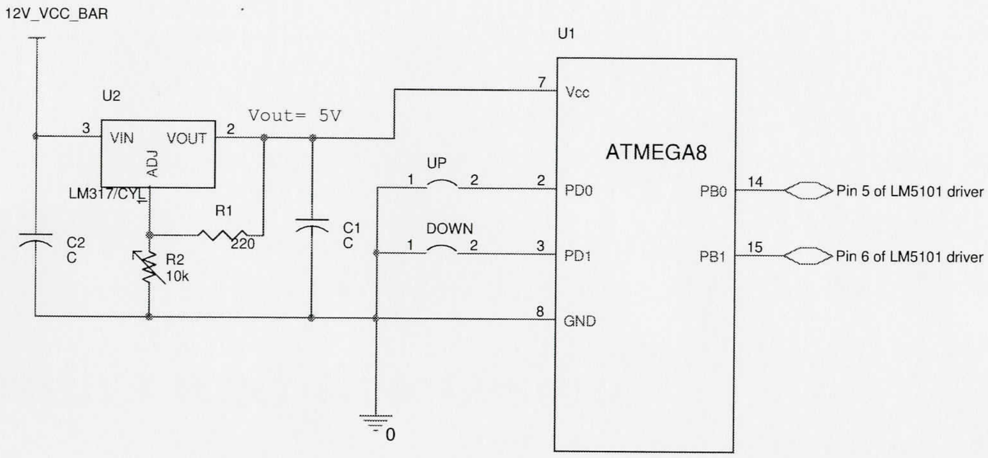
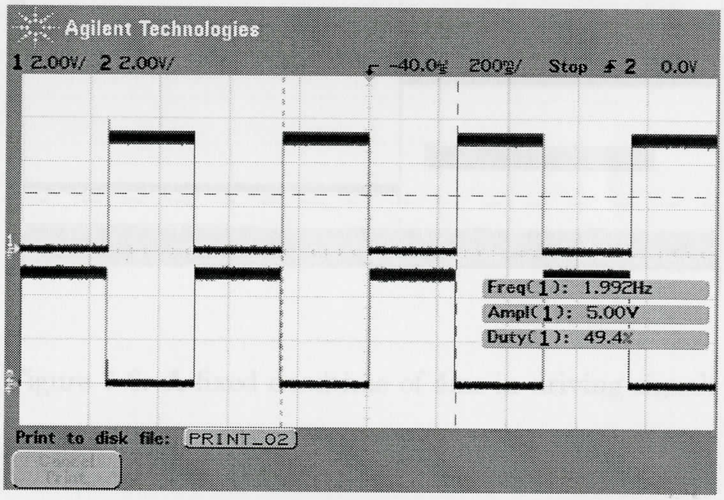


Figure 7-4: Signals generated using the Atmel microcontroller

The frequency is varied by pressing the push-button in pin 2 and 3.



Freq(1): 1.992Hz
Ampl(1): 5.00V
Duty(1): 49.4%

Figure 7-5: The 2 driving signals, which are 180 ° out of phase

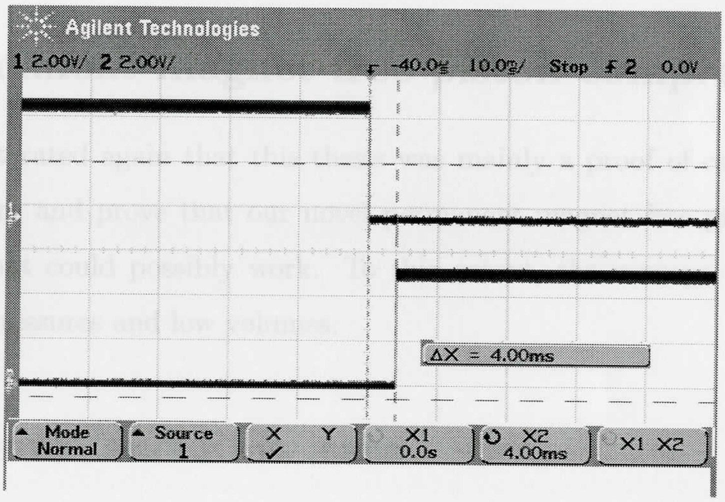


Figure 7-6: A fixed deadtime of 4ms in driving signals

Chapter 8

Results and discussion

8.1 Permanent magnet free piston compressor

It should be reiterated again that this thesis was mainly a proof of concept. The aim was simply to try and prove that our novel permanent magnet free piston compressor (PMFPC) concept could possibly work. To this extent, the concept was proved adequately at low pressures and low volumes.

8.2 Pressure and Flow rate

The flow rate of the PMFPC at zero pressure was measured empirically through the following procedure:

- 5Litre bucket full of water.
- 1.5Litre bottle filled with water from the 5Litre bucket then turned upside down.
- This 1.5Litre bottle was held at the surface (water level) of the 5Litre bucket so that the mouth of the bottle is slightly immersed in water.
- The high pressure outlet of the PMFPC is inserted in a bottle.
- As the PMFPC is turned on, the stopwatch is used to time how long it took for the bottle to empty onto the bucket and with the known volume of water in a bottle,

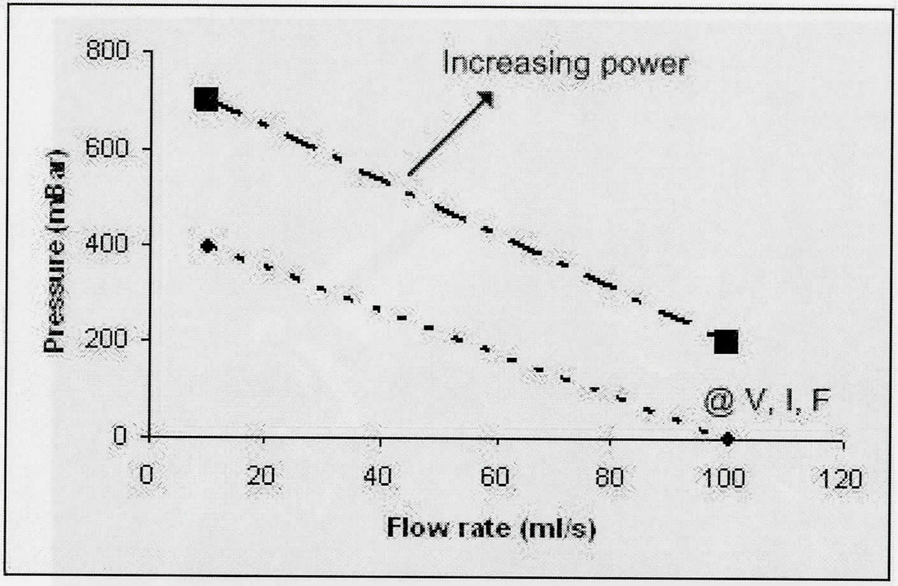


Figure 8-1: Pressure vs flow rate graph

the flow rate was therefore calculated.

The pressure measurements were obtained using a Digital Manometer.

Although this pressure/volume is not sufficient for a real refrigerator, these results were considered more than adequate as proof of concept for this thesis. The final chapter discusses further work to take this concept further.

8.3 Force

After designing the linear motor, the important parameter that needed to be measured was the force. As a result, the measured force compared with the calculated force. The force was empirically measured by attaching the string from a permanent magnet of the linear motor via the bearing to the spring balance. The bearing was used because the spring balance is used vertically for accuracy. The DC current is applied to the linear motor so that it pulls the spring balance resulting in the force being recorded.

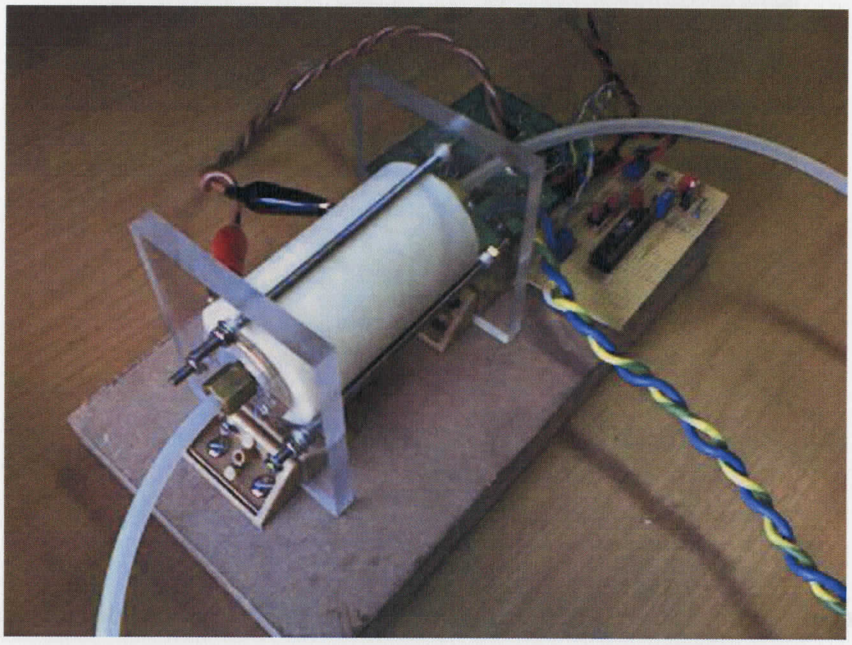


Figure 8-2: A complete permanent magnet piston compressor

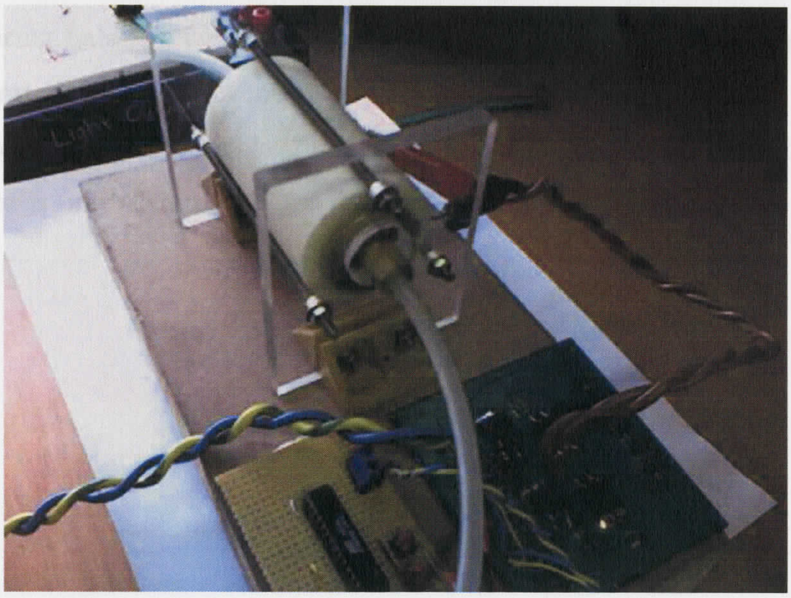


Figure 8-3: A complete compressor with the driving circuitry

Figure 8-4: A compressor in action, shown by pumping compressed air through water in a bottle

There were limitations for testing higher forces due to the measuring instrument capability. However, the motor constant which is called Figure of Merit (FOM) in linear motor was found to be 5.1 N/ W as shown from Figure 8-7. The measuring instrument used was a spring balance, whereby the deflection of force is shown by a slider(pointer) along a calibrated scale. This means that for higher forces, the slider travels longer distance, therefore, it is impossible to measure higher forces because the stroke length of the compressor is only 25 mm.

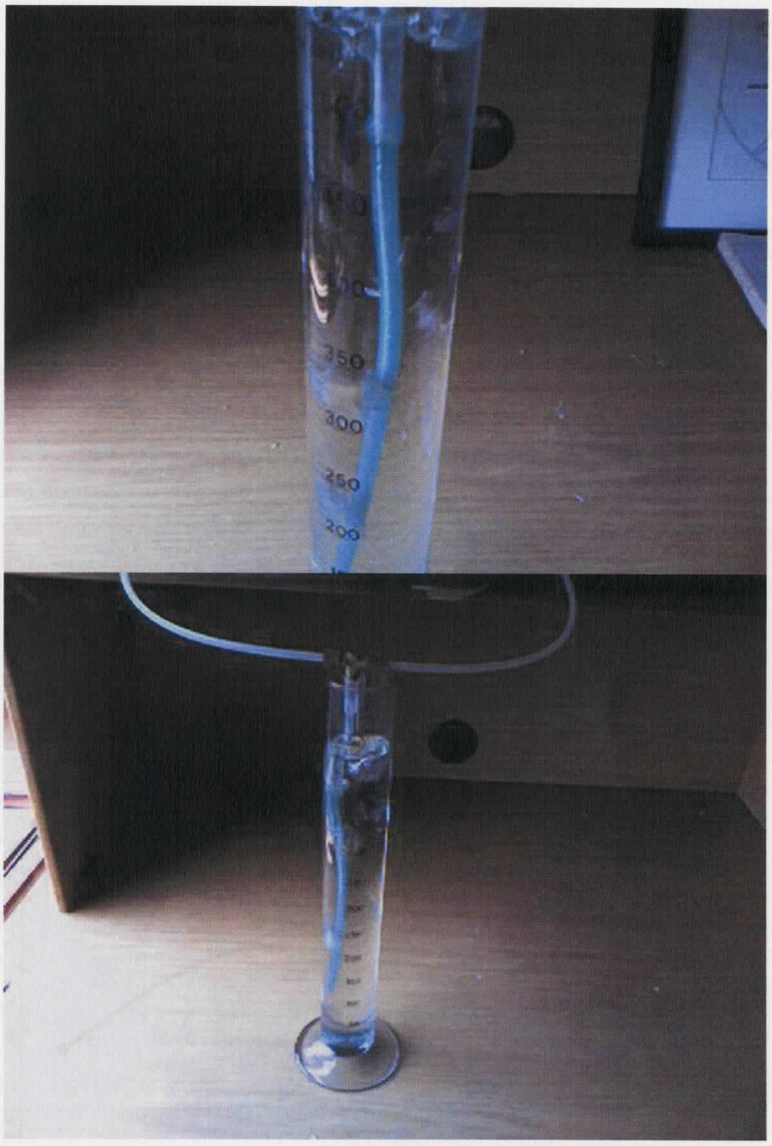


Figure 8-5: High pressure outlet pipe immersed in water; bubbles are produced

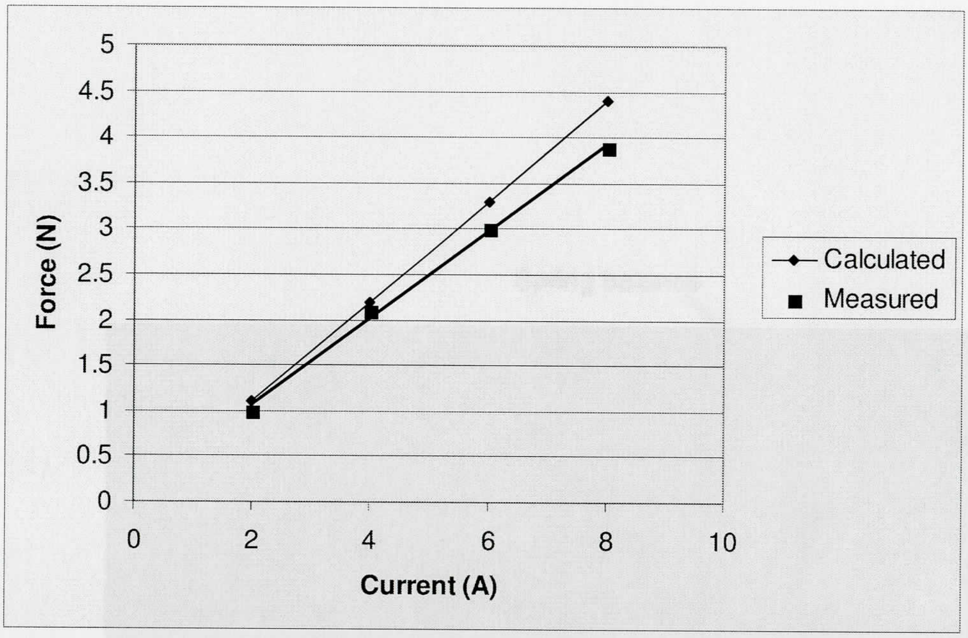


Figure 8-6: thrust vs current graph

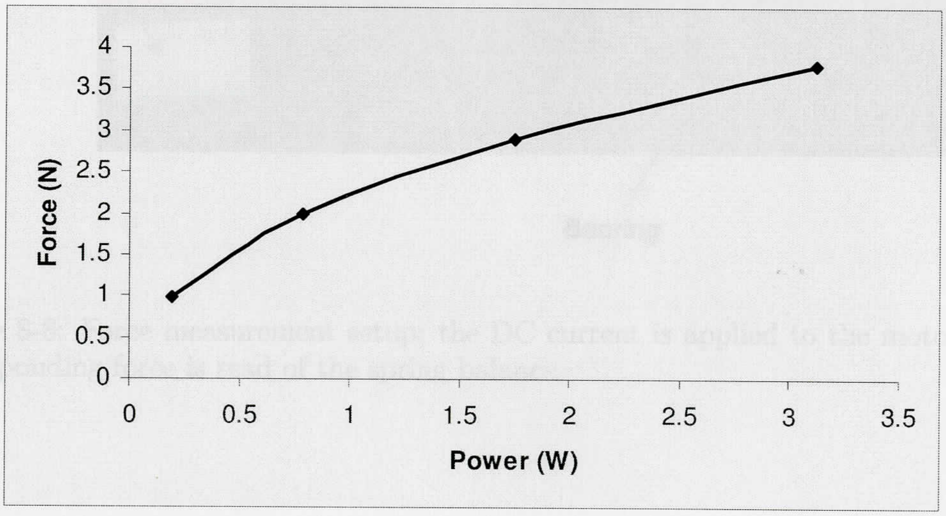


Figure 8-7: Force vs power graph showing the Figure of Merit (FOM) at 1N to be 5.1 N/W

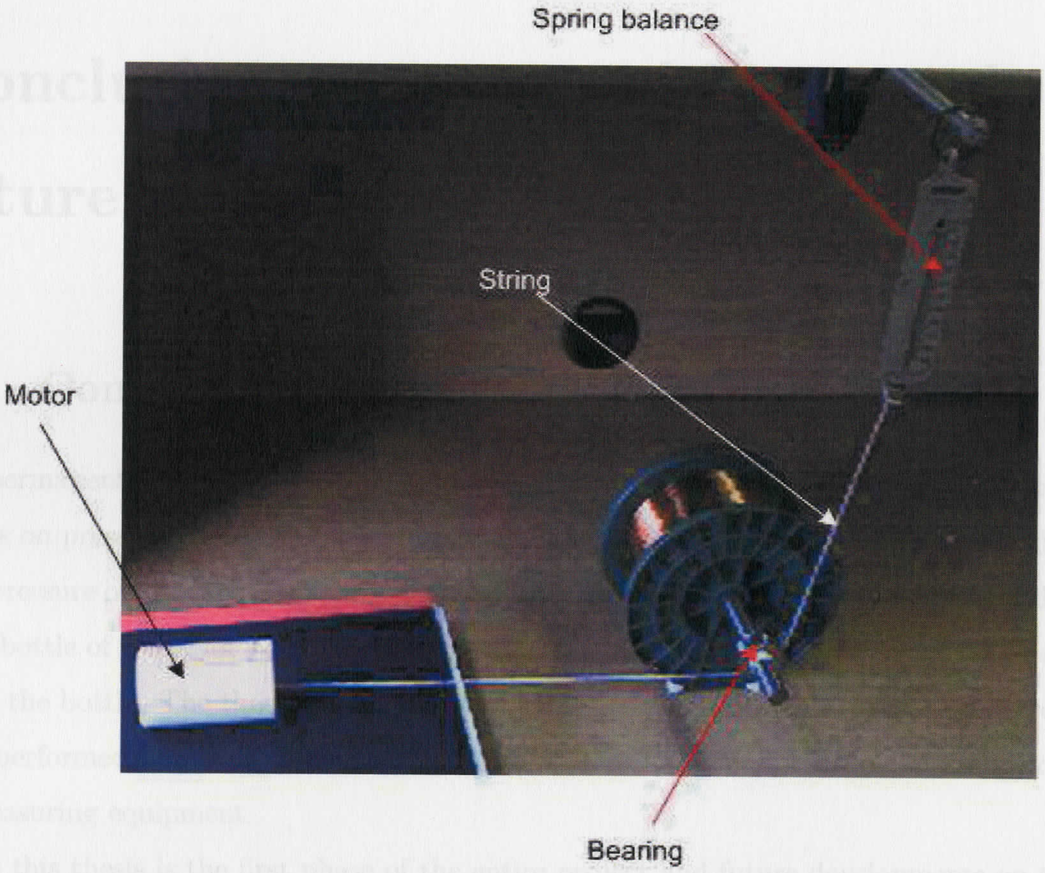


Figure 8-8: Force measurement setup; the DC current is applied to the motor and the corresponding force is read of the spring balance

Chapter 9

Conclusion, recommendations and future work

9.1 Conclusion

The permanent magnet piston compressor was successfully constructed, however, experiments on pressure could not be performed due to the incomplete test setup, although a high pressure outlet pipe from the permanent magnet piston compressor was immersed in a full bottle of water for demonstration purposes, whereby intense bubbles could be seen inside the bottle. The theoretical and experimental relationship with thrust and current were performed, however, tests on higher forces were not conducted due to limitations on measuring equipment.

As this thesis is the first phase of the entire project and future developments on the project are listed in the future work section. This work is a proof of concept phase and, as a result, it should be seen as a basis for the on-going project.

9.2 Recommendations

During the development of this project, the linear motor was found to have vast applications besides being used as a compressor. It can be used as a mechanical actuator for position control purposes and this may replace the hydraulic actuator and it can also be used as an ultrasonic transducer. The other interesting application which was discovered, is in the medical field where the compressor can be used to supply oil-free air. As a result, it is recommended that these other applications be explored.

9.3 Future work

The scope of the project was limited to a phase where the permanent magnet piston compressor was designed to pump air. Therefore, the ultimate goals are to improve and optimize the design to a stage where it is developed so that it can be used in a refrigerator system. Initial research has been done and has shown that the project is feasible up to the final phase as a commercial product in the refrigeration industry.

The following outlines a few areas for future development.

9.3.1 Closed loop mode

The designed compressor was only tested on open loop mode where the frequency was varied manually with the varying load (pressure). As part of future work, the compressor will be run on closed loop mode. The feedback signals will be obtained by a hall effect sensor mounted on both sides of the motor. This will be done to determine the position of the permanent magnet (piston).

9.3.2 Increasing force

Force can be increased in various ways:

Diameter reduction

The diameter of the piston needs to be decreased by at least half the size in order to yield a higher force, as force is the product of pressure and area, therefore, this will result in higher pressure. Again, decreasing the diameter with the same stroke will also mean less clearance volume, which will result in better volumetric efficiency and less piston leakage.

Addition of iron powder or ferrite

During the formation of the enclosure (cylinder), iron powder or ferrite will be added to the thermoplastic material. This will result in improving and containing the flux path. The relative permeability μ_r of iron is 5000, therefore, this is much higher as compared to the permeability of air, which is 1.

Increasing the number of poles

At present, linear motor has two poles, therefore, having more than two poles will yield in higher forces.

Stronger permanent magnet

At present, there are already higher grade permanent magnets than the ones (N35) that the researcher used in the development of a compressor, which are available on the market which are N55 and N65.

9.3.3 Valves improvement

By improving the valve tolerances, leakage losses are decreased. Better dynamic performance of the valves is achieved by damping their oscillation. Flapper valves made out of stainless steel seemed to be the best set of valves in terms of performance and cost.

9.3.4 Vibration reduction

To reduce oscillation, two compressors can be constructed to work in counteraction to one another.

9.4 Final note

The project has been successfully demonstrated as a working proof of concept of the novel compressor. It has shown that it has potential to work as a refrigerator compressor, as well as other applications. It should be pursued further in terms of research and development and could be used in personal refrigerators in the future.

During the development of this project, it won some prizes and achievements, namely:

- The innovative nature of this project made it possible for a patent to be filed. The reference number for the application is V16803 and it was filed on the 18th of May 2005.

- It won first prize at a local Innovation Fund competition, which was held by the Cape Peninsula University of Technology (CPUT) (formerly Cape Technikon) and continued to be nominated among the top 12 projects at national level.

- This project received recognition from the SABS Prototype Awards as a project with lots of potential but could not win any prize because it was incomplete at the time of the competition.

- It was exhibited at an IEEE student exhibition held in Kenya and managed to obtain second prize. This exhibition was created to create a culture of innovation in the region of East Africa, which faces several economic and political challenges.

Bibliography

[1] Anon. n.d. China permanent magnet ltd [Online].
Available: http://www.permanentmagnet.com/history.html.
[03 October 2004].

[2] Anon. 1998. The schumacher centre for technology and development. *Refrigeration for developing countries.* Technical report.

[3] Anon. n.d. Magnet and magnetism [Online].
Available: http://www.matchrockets.com/ether/magfqs.html.
[20 June 2004].

[4] Anon. n.d. Shin-etsu chemical co. ltd [Online]
Available: http://shinetsurareearthmagnet.jp/e/design/index.html.
[20 June 2004].

[5] Anon. n.d. Total magnetics solutions inc *Magnet designs and standards*. [Online].
Available: http://www.magnetsales.com/design/designg2.html.
[23 may 2005].

[6] Anon. n.d. Sunpower inc. [Online]
Available: http://www.sunpower.com/technology/cryo.html.
[24 June 2004].

[7] Anon. n.d. Global cooling inc. [Online]
Available: http://globalcooling.com/howitworks.html.
[25 February 2004].

[8] Basak, A. 1996. *Permanent-magnet DC linear motors*. New York: Oxford.

[9] Beale, W., Van der Walt, N. & Unger, R. 1996. *Free piston end position limiter.* US patent 5537820.

[10] Boldea, I. & Nasar, S. 1985. *Linear motion electromagnetic systems.* New York: Wiley.

[11] Cook, N. 1995. *Refrigeration and air-conditioning technology.* London: Macmillan.

[12] De Lange, E. 1999. *Low cost refrigeration for RDSM.* Eskom confidential report. RES/M1/99/01313.

[13] Dossat, R. 1981. *Principles of refrigeration.* 2nd ed. New York: Wiley.

[14] Du Broff, R., Marshal, S. & Skitek, G. 1996. *Electromagnetic concepts and applications.* 4th ed. Englewood Cliffs: Prentice Hall.

[15] ENGEL. n.d. *Swing compressor.* Patent JP 2004293558.

[16] Enslin, J. 2005. Consultant engineer at ABB. (Verbal consultation). Email: johan.enslin@za.abb.com.

[17] Gurrapa, I. 2003. Corrosion characteristics of permanent magnets in acidic environments. *Journal of alloys and compounds,* vol. 360: 236-242.

[18] Hanselman, D. 2003. *Brushless permanent magnet motor design.* 2nd ed. Rhodes Island: Cranston.

[19] Haywood, D. n.d. An introduction to stirling cycle machines. [Online].
Available: http://www.mech.canterbury.ac.nz/research/stirling/scintro.pdf.
[12 march 2003].

[20] Hendershot, J. 1994. *Design of brushless permanent magnet motors.* Ohio: Magna physics.

[21] Hoang, V. 2003. *Design of a single-sided linear induction motor.* [published Masters thesis] Brisbane, University of Queensland.

[22] Inagaki, k. & Morita, I. 2003. *Linear motor and linear compressor.* US patent 20030173836.

[23] Janssen, M & Beks, P. n.d. Measurements and application of performance characteristics of a free piston stirling cooler. [Online]. *http://www. globalcooling.nl/papers/regent2002.pdf.*
[18 March 2003].

[24] Keiter, D. & Unger, R. 2001. *DC centering of free piston machine.* US patent 6199381.

[25] Koelet, P. 1992. *Industrial refrigeration, principle design and applications.* London: Macmillan.

[26] Kraus, J. 1992. *Electromagnetics.* 4th ed. New York: Mcgraw-Hill.

[27] Macdermont, C. & Shenoy, A. 1997. *Selecting thermoplastics for engineering applications.* 2nd ed. New York: Marcel Dekker.

[28] Moran, M & Shapiro, H. 2000. *Fundamentals of engineering thermodynamics.* 4th ed. New York: Wiley.

[29] Morita, I. et al. 2003. *Linear compressor.* US patent 6575716.

[30] Popham, V., Lawrenson, C. & Burr, R (ed). 2001. Variable gap-reluctance linear motor with application to linear resonance compressors. *Proceedings of 2001 ASME international mechanical engineering congress and exposition.*

[31] Porkhial, S., Khastoo, B. & Modarres, M. 2002. Transients characteristics of reciprocating compressors in household refrigerators. *Applied thermal engineering,* vol. 32: 1391-1402.

[32] Radermacher, R. & Kim, K. 1996. Domestic refrigerators: recent development. *International journal of refrigeration,* vol. 19: 61-69.

[33] Redlich, R. 1994. *Method and apparatus for measuring piston position in a free piston compressor.* US patent 5342176.

[34] Sen, P. 1997. *Principles of electrical machines and power electronics.* 2nd ed. New York: Wiley and Sons.

[35] Seo, K. 2000. *Linear compressor.* US patent 6089836.

[36] Trout, S. (ed). n.d. Material selection of permanent magnet, considering thermal properties correctly. [Online]
Available:http://www.arnoldmagnetics.com/mtc/pdf/strout/material/selection/cw2001.pdf.\
[26 July 2005]

[37] Whitman, W. & Johnson. 1991. *Refrigeration and air-conditioning technology: concepts, procedures and trouble-shooting.* New York: Delmar.

Appendix A

Refrigeration calculations

A.1 Mass flow rate

To calculate the mass flow rate required for 50W cooling capacity as specified by Eskom. COP was said to be: $2.5 \leq COP \leq 5$. therefore asuming COP of 3.5. The refrigerant used is R134a. The condensing temperaure 40 °Cis while the evaporating temperature is -10 °C, these temperatures correspond with 10 bar and 2 bar respectively from the $p - h$ diagram of R134a.

$$PV = mRT$$

To calculate m from initial conditions:

Volume of the our cylinder is calculated with the stroke length of 20 mm.

$$m = \frac{200\times10^{3}\,\mathrm{Pa}\times7.604\times10^{-6}\,\mathrm{m}^{2}}{76.13\times263\,\mathrm{K}}$$

$$= 76\times10^{-6} kg/s \qquad \text{(for our system)}$$

Therefore for cooling capacity of 50 W × 3.5 = 175W= 175 J/s

Mass flow rate needed for 50W

$\frac{W}{h_{fg}} = \frac{175J/s}{205.56kJ/kg} = 0.851kg/s$ (note: h_{fg} is correspond with -10 °C from p-h diagram.

therefore: $\frac{0.851\times10^{-3}}{76.6\times10^{-6}} = 11.12 = frequency \times no.of strokes$

5.55 cycles per second is the frequency need for our compressor to be able pump the mass flow rate for 50W cooling capacity.

A.2 Power required for compression

This the power needed for one throw on one chamber upto a pint where the vapouri s just about to be pushed out. The compression ratio is assummed to 5.

$$w = \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{76.9\times10^{-6}\times76.13\times263\times1.166}{1.166-1} \left[\left(\frac{10}{2} \right)^{\frac{1.166-1}{1.166}} - 1 \right]$$

$$= 2.75J$$

A.3 Outlet temperature

It is important to calculate the outlet temperature for adiabatic compression. An adiabatic compression means that all the heat of compression is retained in a gas being compressed (no heat is added or subtracted). We assume $n = k$.

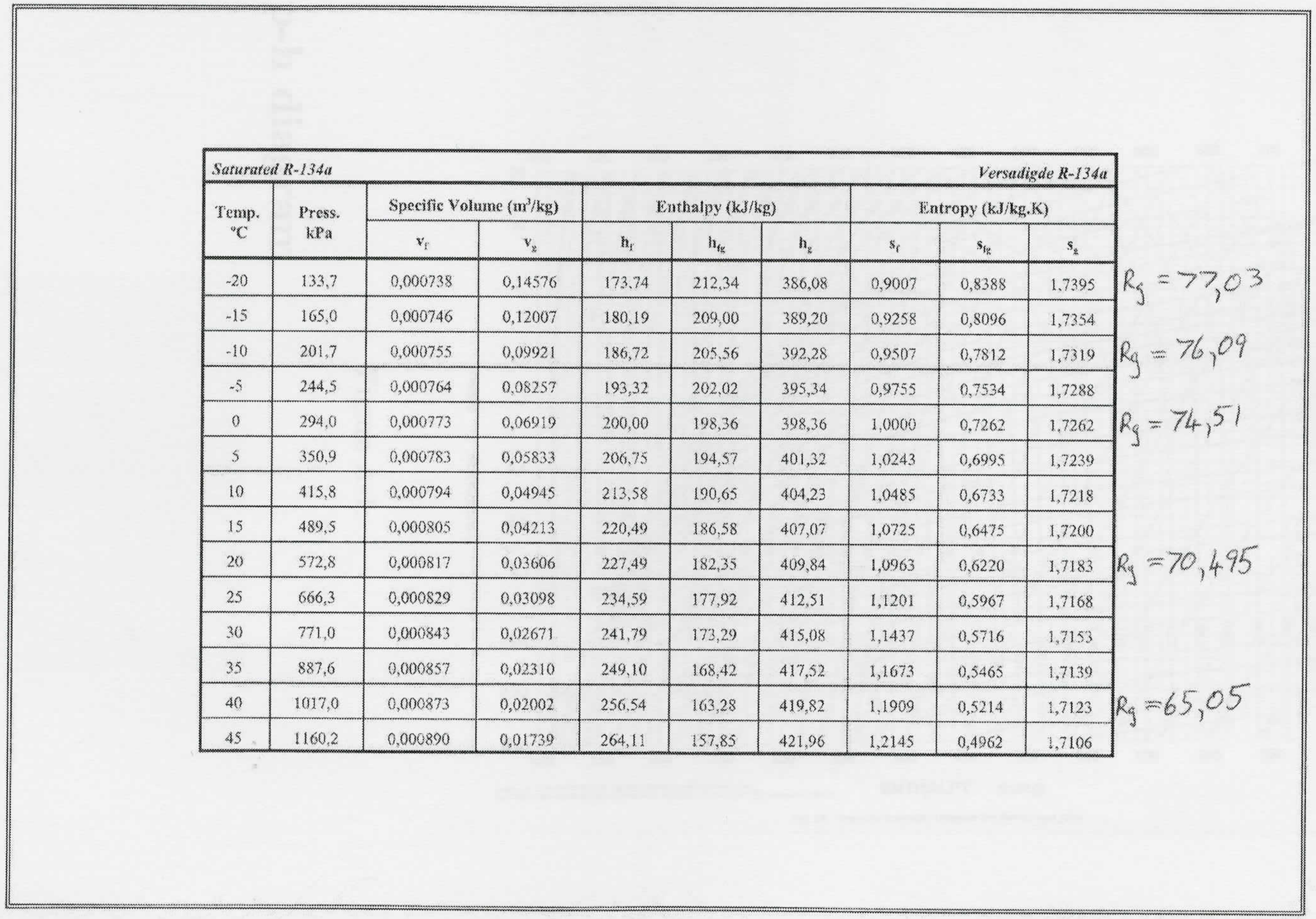
$$T_2 = \left[T_1^k \left(\frac{P_2}{P_1} \right)^{k-1} \right]^{\frac{1}{k}}$$

$$T_2 = \left[253^{1.166} \left(\frac{10}{2} \right)^{1.166-1} \right]^{\frac{1}{1.166}}$$

$$= 330.65K = 57.7\,^{\circ}\mathrm{C}$$

Note: Final Temperature is 57.7 °C which is greater than saturation temperature (T_{sat} = 40 °C) from the Table ?? This means the gas is superheated which means it stays near perfect gas as a results all assumption are correct [16].

A.4 Saturated conditions of R134a



Saturated R-134a *Versadigde R-134a*

Temp. °C	Press. kPa	Specific Volume (m³/kg)		Enthalpy (kJ/kg)			Entropy (kJ/kg.K)			
		v_f	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
-20	133,7	0,000738	0,14576	173,74	212,34	386,08	0,9007	0,8388	1,7395	$R_g = 77,03$
-15	165,0	0,000746	0,12007	180,19	209,00	389,20	0,9258	0,8096	1,7354	
-10	201,7	0,000755	0,09921	186,72	205,56	392,28	0,9507	0,7812	1,7319	$R_g = 76,09$
-5	244,5	0,000764	0,08257	193,32	202,02	395,34	0,9755	0,7534	1,7288	
0	294,0	0,000773	0,06919	200,00	198,36	398,36	1,0000	0,7262	1,7262	$R_g = 74,51$
5	350,9	0,000783	0,05833	206,75	194,57	401,32	1,0243	0,6995	1,7239	
10	415,8	0,000794	0,04945	213,58	190,65	404,23	1,0485	0,6733	1,7218	
15	489,5	0,000805	0,04213	220,49	186,58	407,07	1,0725	0,6475	1,7200	
20	572,8	0,000817	0,03606	227,49	182,35	409,84	1,0963	0,6220	1,7183	$R_g = 70,495$
25	666,3	0,000829	0,03098	234,59	177,92	412,51	1,1201	0,5967	1,7168	
30	771,0	0,000843	0,02671	241,79	173,29	415,08	1,1437	0,5716	1,7153	
35	887,6	0,000857	0,02310	249,10	168,42	417,52	1,1673	0,5465	1,7139	
40	1017,0	0,000873	0,02002	256,54	163,28	419,82	1,1909	0,5214	1,7123	$R_g = 65,05$
45	1160,2	0,000890	0,01739	264,11	157,85	421,96	1,2145	0,4962	1,7106	

p-h table for R134a under saturated condtions.

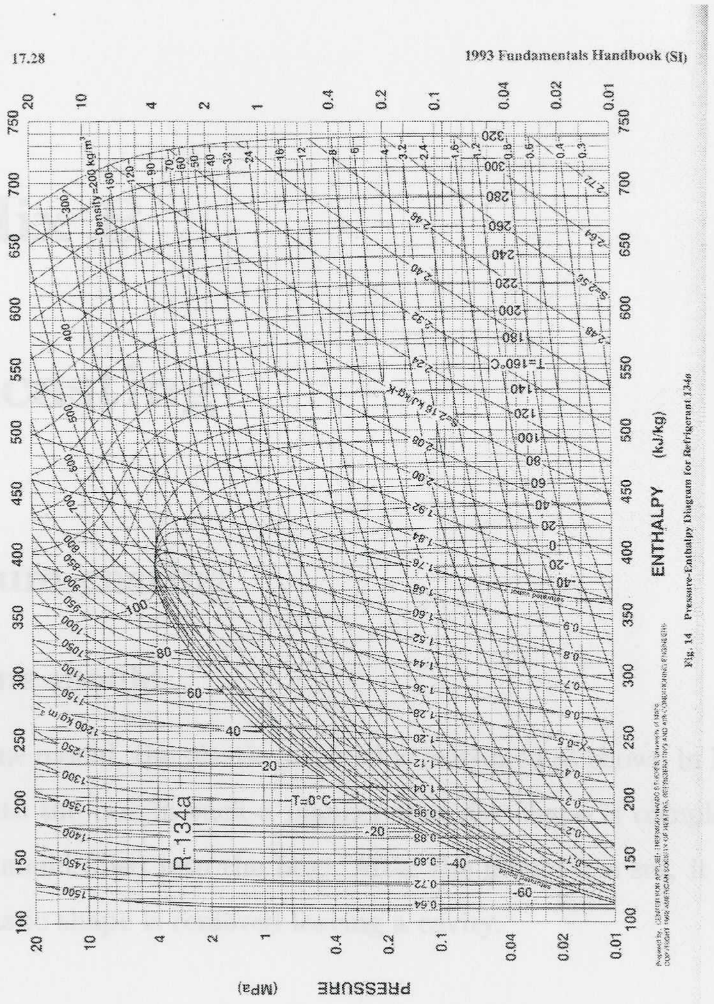


Figure A-1:

A.5 p-h diagram

Appendix B

Plastic casting

B.1 Vacuum casting

B.1.1 Silicone mould

To make the silicone mould, the plastic material is machined as shown in Figure B-1.This shape is placed into the box in such a manner that the shape is completely inside the box, the silicone mould filled into the box. After the mould has set, it is cut into two halves and the plastic shape is removed leaving a cavity.

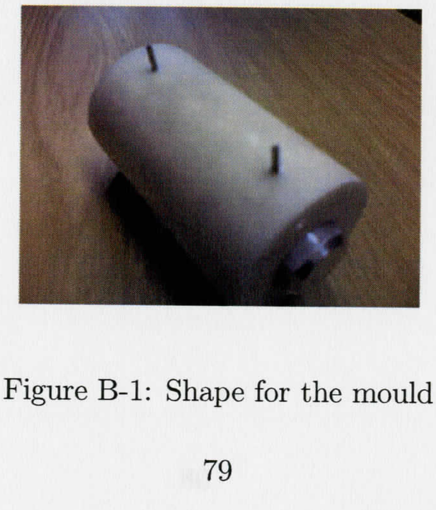


Figure B-1: Shape for the mould

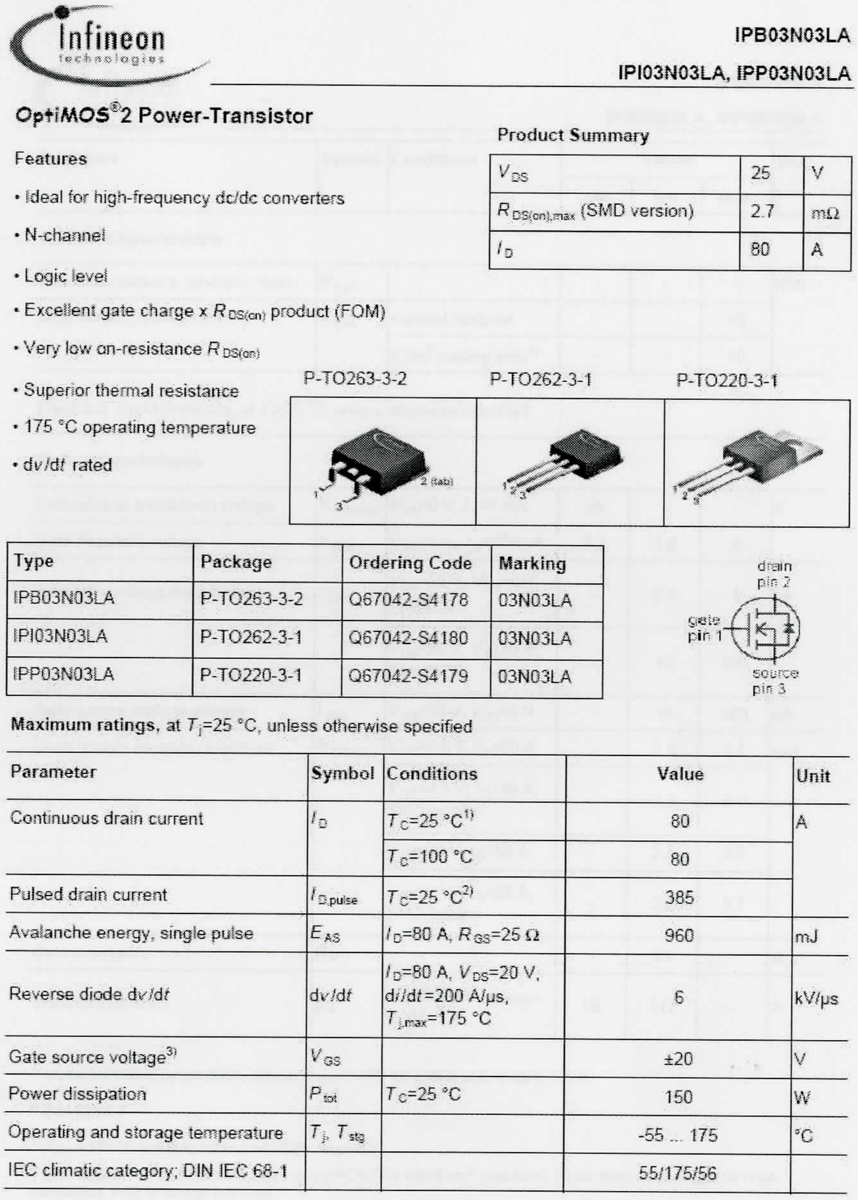
Appendix C

Data sheets

C.1 MOSFETs

C.2 MOSFET driver

C.3 Atmel



Infineon technologies

IPB03N03LA

IPI03N03LA, IPP03N03LA

OptiMOS®2 Power-Transistor

Product Summary

V_{DS}	25	V
$R_{DS(on),max}$ (SMD version)	2.7	mΩ
I_D	80	A

Features

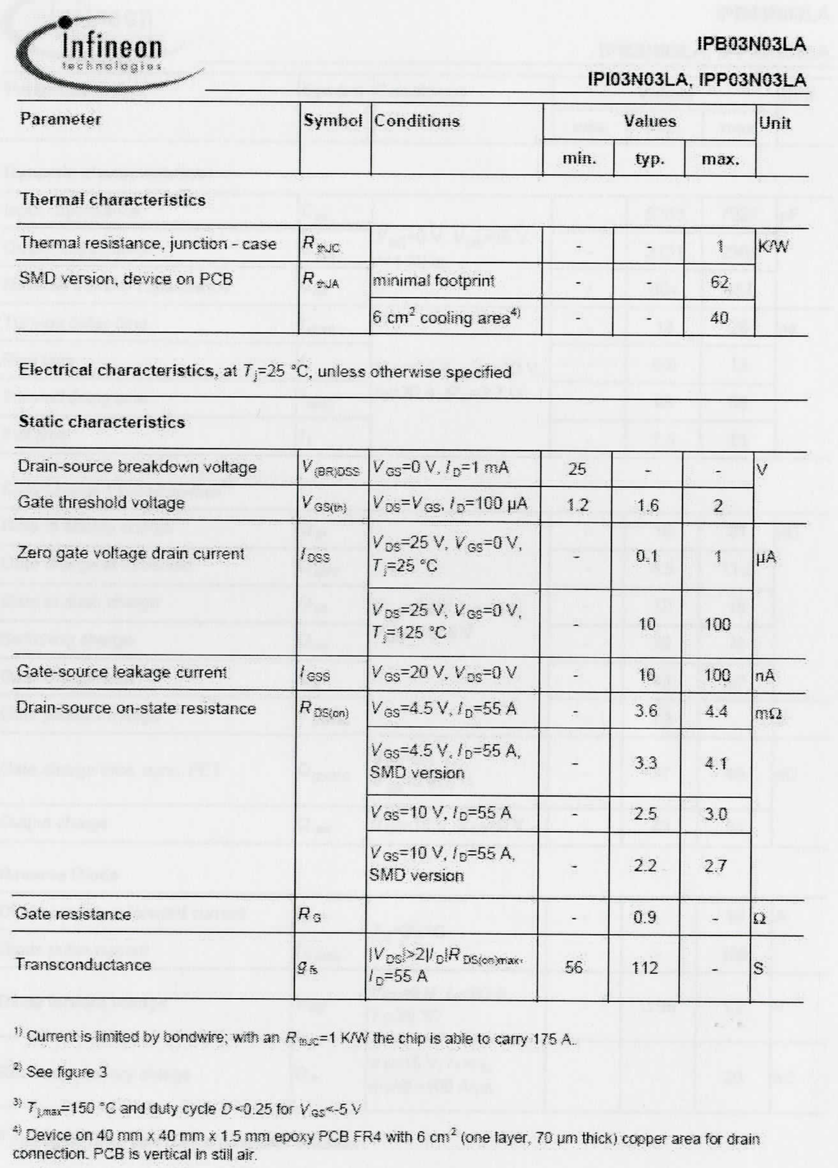
- Ideal for high-frequency dc/dc converters
- N-channel
- Logic level
- Excellent gate charge x $R_{DS(on)}$ product (FOM)
- Very low on-resistance $R_{DS(on)}$
- Superior thermal resistance
- 175 °C operating temperature
- dv/dt rated

Type	Package	Ordering Code	Marking
IPB03N03LA	P-TO263-3-2	Q67042-S4178	03N03LA
IPI03N03LA	P-TO262-3-1	Q67042-S4180	03N03LA
IPP03N03LA	P-TO220-3-1	Q67042-S4179	03N03LA

Maximum ratings, at T_j=25 °C, unless otherwise specified

Parameter	Symbol	Conditions	Value	Unit
Continuous drain current	I_D	T_C=25 °C[1]	80	A
		T_C=100 °C	80	
Pulsed drain current	$I_{D,pulse}$	T_C=25 °C[2]	385	
Avalanche energy, single pulse	E_{AS}	I_D=80 A, R_{GS}=25 Ω	960	mJ
Reverse diode dv/dt	dv/dt	I_D=80 A, V_{DS}=20 V, di/dt=200 A/µs, $T_{j,max}$=175 °C	6	kV/µs
Gate source voltage[3]	V_{GS}		±20	V
Power dissipation	P_{tot}	T_C=25 °C	150	W
Operating and storage temperature	T_j, T_{stg}		-55 ... 175	°C
IEC climatic category; DIN IEC 68-1			55/175/56	

Figure C-1:



Infineon technologies

IPB03N03LA

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Parameter	Symbol	Conditions	Values			Unit
			min.	typ.	max.	
Thermal characteristics						
Thermal resistance, junction - case	R_{thJC}		-	-	1	K/W
SMD version, device on PCB	R_{thJA}	minimal footprint	-	-	62	
		6 cm² cooling area[4]	-	-	40	

Electrical characteristics, at T_j=25 °C, unless otherwise specified

Parameter	Symbol	Conditions	min.	typ.	max.	Unit
Static characteristics						
Drain-source breakdown voltage	$V_{(BR)DSS}$	V_{GS}=0 V, I_D=1 mA	25	-	-	V
Gate threshold voltage	$V_{GS(th)}$	V_{DS}=V_{GS}, I_D=100 µA	1.2	1.6	2	
Zero gate voltage drain current	I_{DSS}	V_{DS}=25 V, V_{GS}=0 V, T_j=25 °C	-	0.1	1	µA
		V_{DS}=25 V, V_{GS}=0 V, T_j=125 °C	-	10	100	
Gate-source leakage current	I_{GSS}	V_{GS}=20 V, V_{DS}=0 V	-	10	100	nA
Drain-source on-state resistance	$R_{DS(on)}$	V_{GS}=4.5 V, I_D=55 A	-	3.6	4.4	mΩ
		V_{GS}=4.5 V, I_D=55 A, SMD version	-	3.3	4.1	
		V_{GS}=10 V, I_D=55 A	-	2.5	3.0	
		V_{GS}=10 V, I_D=55 A, SMD version	-	2.2	2.7	
Gate resistance	R_G		-	0.9	-	Ω
Transconductance	g_{fs}	$\|V_{DS}\|>2\|I_D\|R_{DS(on)max}$, I_D=55 A	56	112	-	S

---

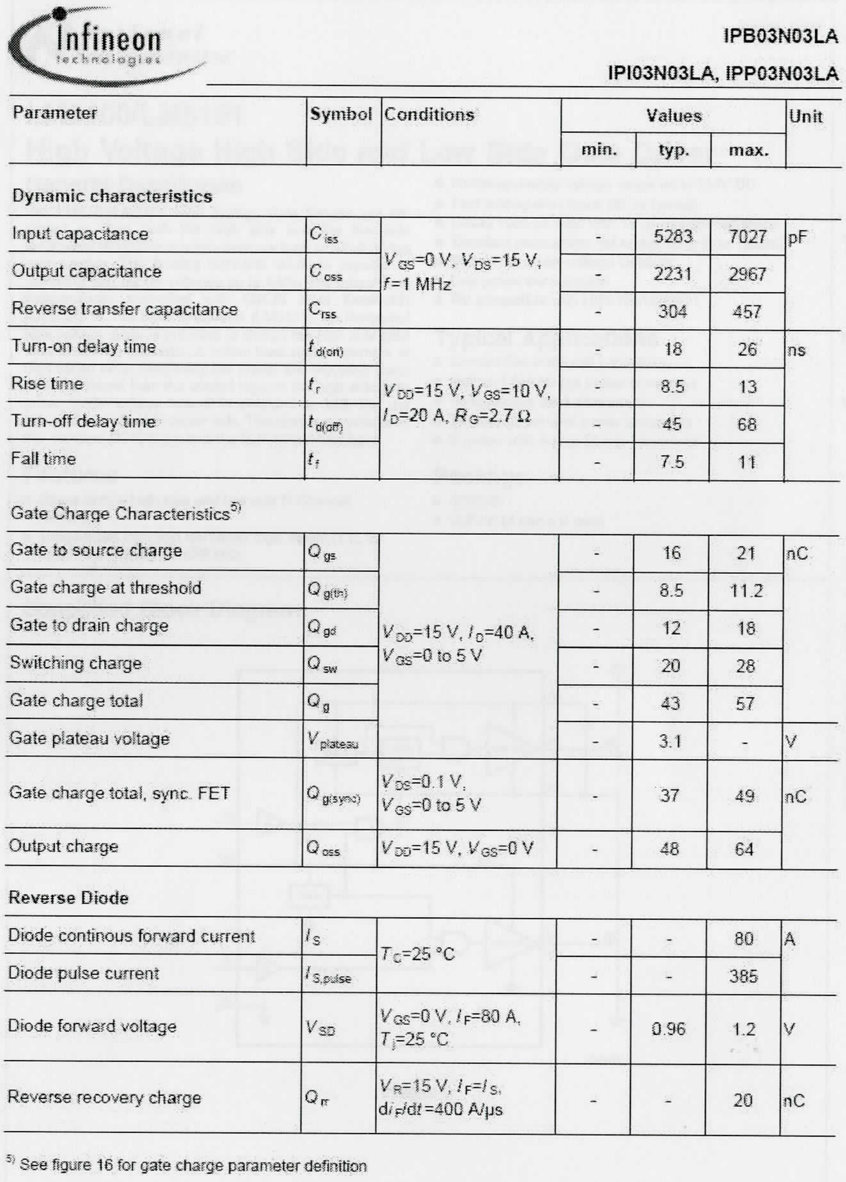
[1] Current is limited by bondwire; with an R_{thJC}=1 K/W the chip is able to carry 175 A.

[2] See figure 3

[3] $T_{j,max}$=150 °C and duty cycle D<0.25 for V_{GS}<-5 V

[4] Device on 40 mm x 40 mm x 1.5 mm epoxy PCB FR4 with 6 cm² (one layer, 70 µm thick) copper area for drain connection. PCB is vertical in still air.

Figure C-2:



Infineon technologies

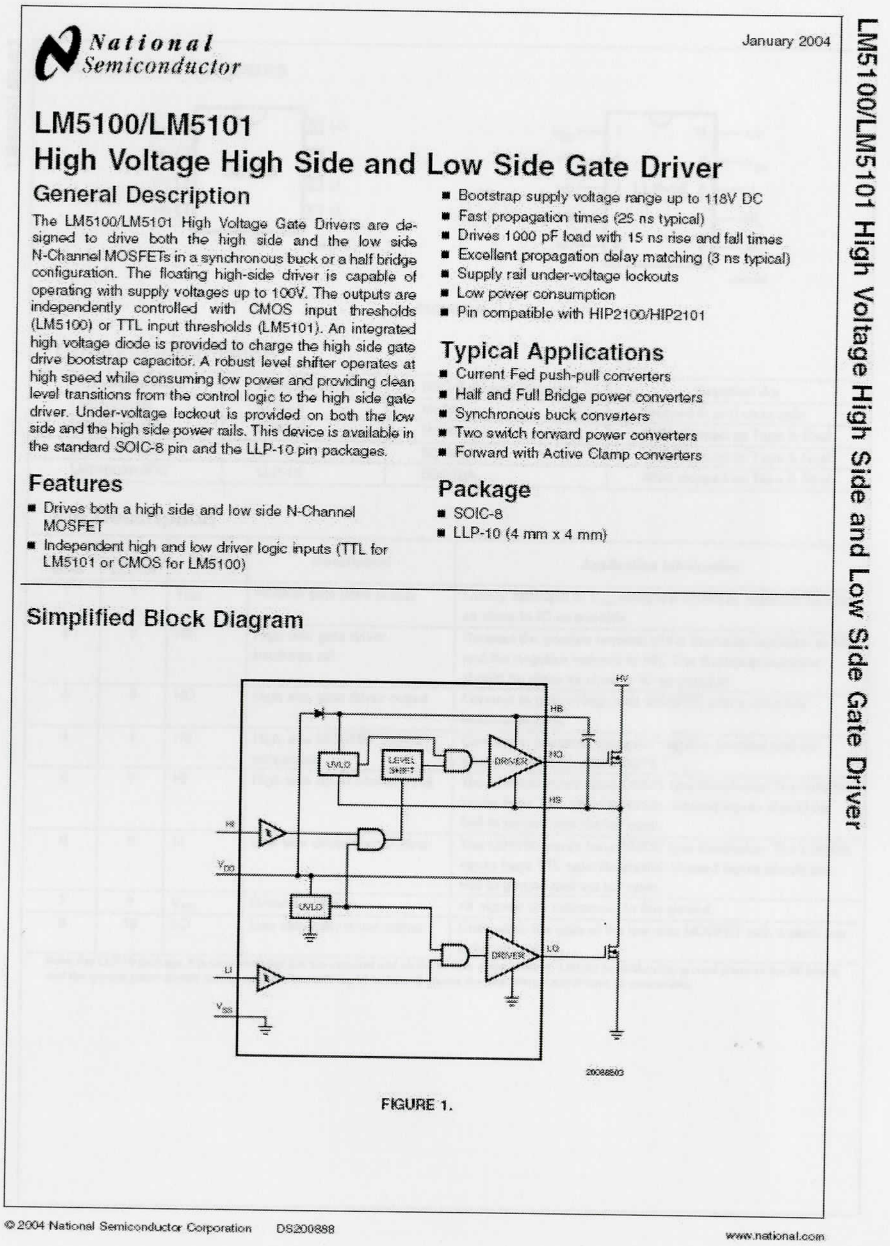
IPB03N03LA

IPI03N03LA, IPP03N03LA

Parameter	Symbol	Conditions	Values			Unit
			min.	typ.	max.	
Dynamic characteristics						
Input capacitance	C_{iss}	V_{GS}=0 V, V_{DS}=15 V, f=1 MHz	-	5283	7027	pF
Output capacitance	C_{oss}		-	2231	2967	
Reverse transfer capacitance	C_{rss}		-	304	457	
Turn-on delay time	$t_{d(on)}$	V_{DD}=15 V, V_{GS}=10 V, I_D=20 A, R_G=2.7 Ω	-	18	26	ns
Rise time	t_r		-	8.5	13	
Turn-off delay time	$t_{d(off)}$		-	45	68	
Fall time	t_f		-	7.5	11	
Gate Charge Characteristics[5]						
Gate to source charge	Q_{gs}	V_{DD}=15 V, I_D=40 A, V_{GS}=0 to 5 V	-	16	21	nC
Gate charge at threshold	$Q_{g(th)}$		-	8.5	11.2	
Gate to drain charge	Q_{gd}		-	12	18	
Switching charge	Q_{sw}		-	20	28	
Gate charge total	Q_g		-	43	57	
Gate plateau voltage	$V_{plateau}$		-	3.1	-	V
Gate charge total, sync. FET	$Q_{g(sync)}$	V_{DS}=0.1 V, V_{GS}=0 to 5 V	-	37	49	nC
Output charge	Q_{oss}	V_{DD}=15 V, V_{GS}=0 V	-	48	64	
Reverse Diode						
Diode continous forward current	I_S	T_C=25 °C	-	-	80	A
Diode pulse current	$I_{S,pulse}$		-	-	385	
Diode forward voltage	V_{SD}	V_{GS}=0 V, I_F=80 A, T_j=25 °C	-	0.96	1.2	V
Reverse recovery charge	Q_{rr}	V_R=15 V, I_F=I_S, di_F/dt=400 A/µs	-	-	20	nC

[5] See figure 16 for gate charge parameter definition

Figure C-3:



National Semiconductor

January 2004

LM5100/LM5101
High Voltage High Side and Low Side Gate Driver

General Description

The LM5100/LM5101 High Voltage Gate Drivers are designed to drive both the high side and the low side N-Channel MOSFETs in a synchronous buck or a half bridge configuration. The floating high-side driver is capable of operating with supply voltages up to 100V. The outputs are independently controlled with CMOS input thresholds (LM5100) or TTL input thresholds (LM5101). An integrated high voltage diode is provided to charge the high side gate drive bootstrap capacitor. A robust level shifter operates at high speed while consuming low power and providing clean level transitions from the control logic to the high side gate driver. Under-voltage lockout is provided on both the low side and the high side power rails. This device is available in the standard SOIC-8 pin and the LLP-10 pin packages.

Features

- Drives both a high side and low side N-Channel MOSFET
- Independent high and low driver logic inputs (TTL for LM5101 or CMOS for LM5100)
- Bootstrap supply voltage range up to 118V DC
- Fast propagation times (25 ns typical)
- Drives 1000 pF load with 15 ns rise and fall times
- Excellent propagation delay matching (3 ns typical)
- Supply rail under-voltage lockouts
- Low power consumption
- Pin compatible with HIP2100/HIP2101

Typical Applications

- Current Fed push-pull converters
- Half and Full Bridge power converters
- Synchronous buck converters
- Two switch forward power converters
- Forward with Active Clamp converters

Package

- SOIC-8
- LLP-10 (4 mm x 4 mm)

Simplified Block Diagram

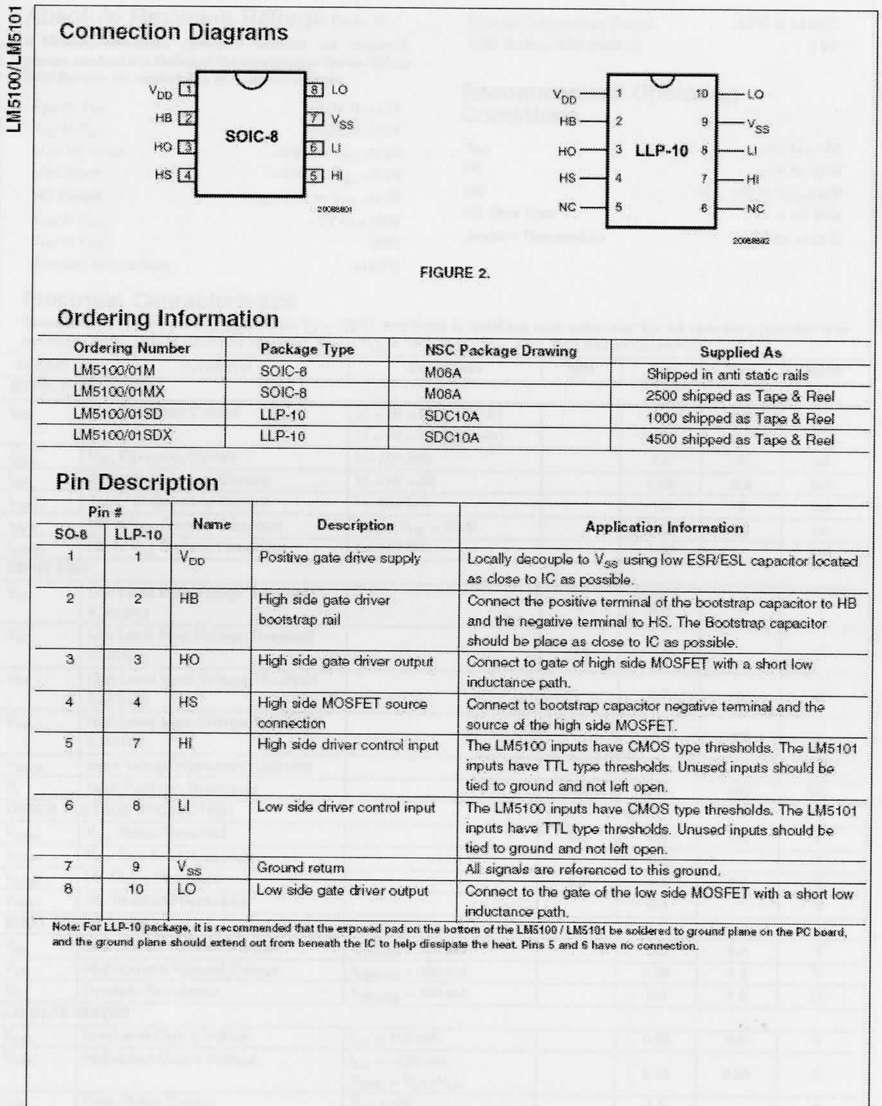
FIGURE 1.

LM5100/LM5101 High Voltage High Side and Low Side Gate Driver

DS200888

www.national.com

Figure C-4:



Connection Diagrams

FIGURE 2.

Ordering Information

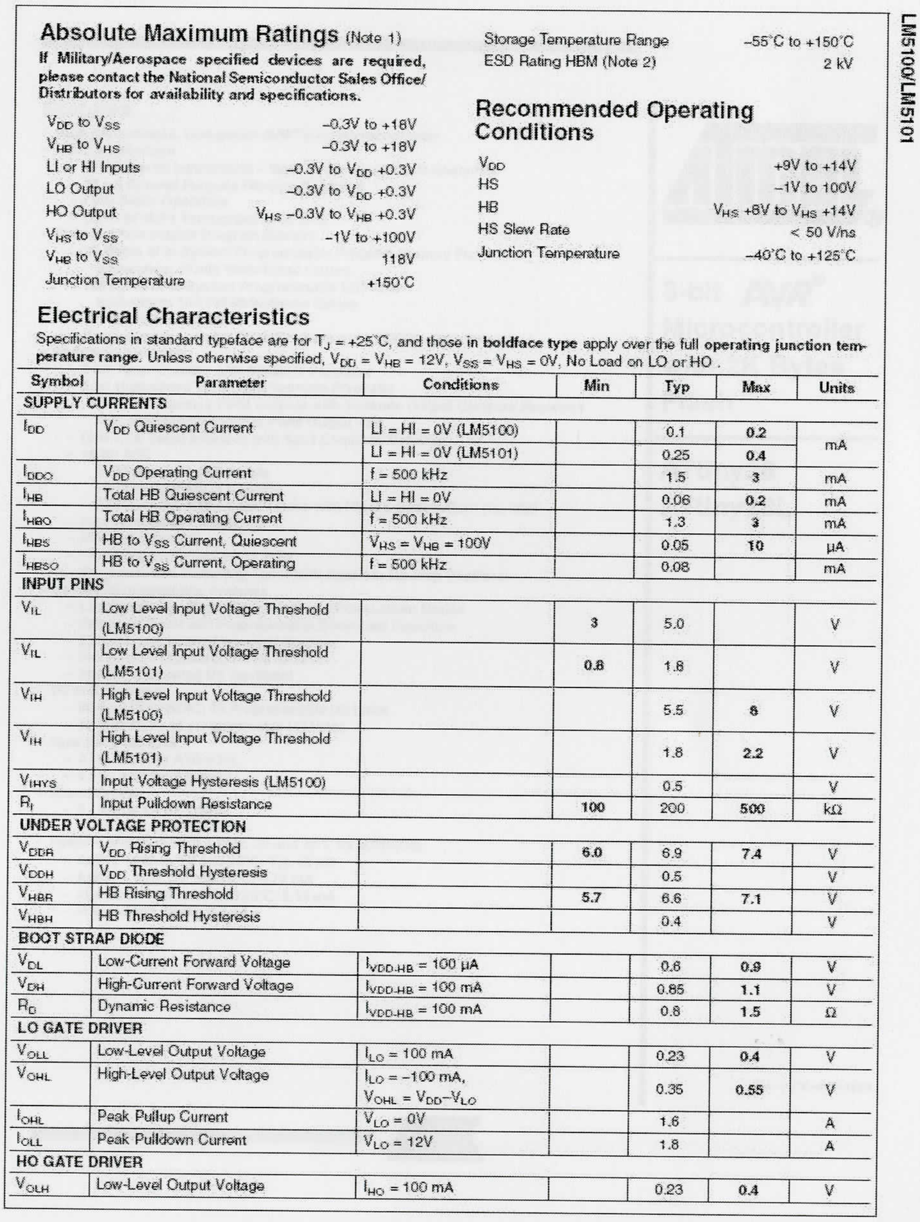
Ordering Number	Package Type	NSC Package Drawing	Supplied As
LM5100/01M	SOIC-8	M08A	Shipped in anti static rails
LM5100/01MX	SOIC-8	M08A	2500 shipped as Tape & Reel
LM5100/01SD	LLP-10	SDC10A	1000 shipped as Tape & Reel
LM5100/01SDX	LLP-10	SDC10A	4500 shipped as Tape & Reel

Pin Description

Pin #		Name	Description	Application Information
SO-8	LLP-10			
1	1	V_{DD}	Positive gate drive supply	Locally decouple to V_{SS} using low ESR/ESL capacitor located as close to IC as possible.
2	2	HB	High side gate driver bootstrap rail	Connect the positive terminal of the bootstrap capacitor to HB and the negative terminal to HS. The Bootstrap capacitor should be place as close to IC as possible.
3	3	HO	High side gate driver output	Connect to gate of high side MOSFET with a short low inductance path.
4	4	HS	High side MOSFET source connection	Connect to bootstrap capacitor negative terminal and the source of the high side MOSFET.
5	7	HI	High side driver control input	The LM5100 inputs have CMOS type thresholds. The LM5101 inputs have TTL type thresholds. Unused inputs should be tied to ground and not left open.
6	8	LI	Low side driver control input	The LM5100 inputs have CMOS type thresholds. The LM5101 inputs have TTL type thresholds. Unused inputs should be tied to ground and not left open.
7	9	V_{SS}	Ground return	All signals are referenced to this ground.
8	10	LO	Low side gate driver output	Connect to the gate of the low side MOSFET with a short low inductance path.

Note: For LLP-10 package, it is recommended that the exposed pad on the bottom of the LM5100 / LM5101 be soldered to ground plane on the PC board, and the ground plane should extend out from beneath the IC to help dissipate the heat. Pins 5 and 6 have no connection.

Figure C-5:



LM5100/LM5101

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

V_{DD} to V_{SS}	–0.3V to +18V
V_{HB} to V_{HS}	–0.3V to +18V
LI or HI Inputs	–0.3V to V_{DD} +0.3V
LO Output	–0.3V to V_{DD} +0.3V
HO Output	V_{HS} –0.3V to V_{HB} +0.3V
V_{HS} to V_{SS}	–1V to +100V
V_{HB} to V_{SS}	118V
Junction Temperature	+150°C
Storage Temperature Range	–55°C to +150°C
ESD Rating HBM (Note 2)	2 kV

Recommended Operating Conditions

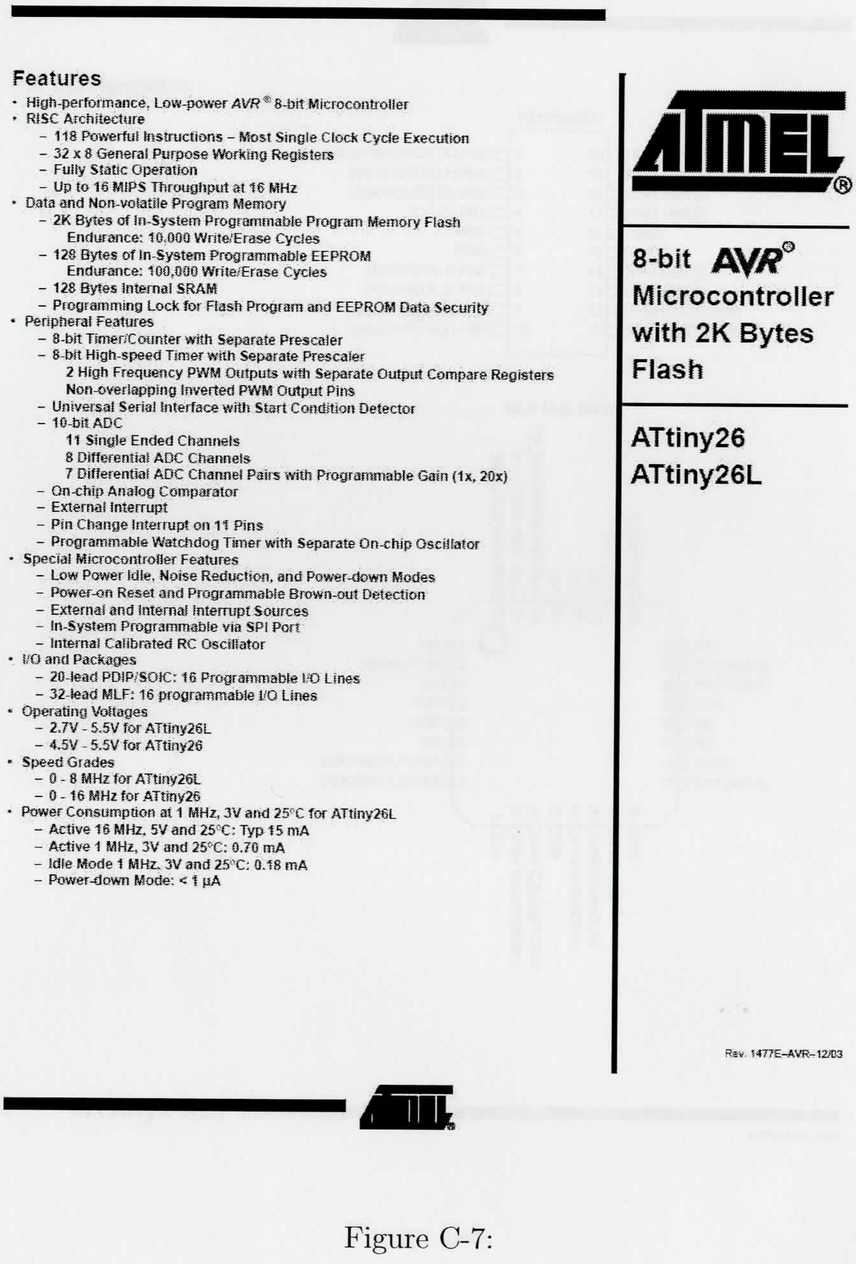
V_{DD}	+9V to +14V
HS	–1V to 100V
HB	V_{HS} +8V to V_{HS} +14V
HS Slew Rate	< 50 V/ns
Junction Temperature	–40°C to +125°C

Electrical Characteristics

Specifications in standard typeface are for $T_J = +25°C$, and those in **boldface type** apply over the full **operating junction temperature range**. Unless otherwise specified, $V_{DD} = V_{HB} = 12V$, $V_{SS} = V_{HS} = 0V$, No Load on LO or HO .

Symbol	Parameter	Conditions	Min	Typ	Max	Units
SUPPLY CURRENTS						
I_{DD}	V_{DD} Quiescent Current	LI = HI = 0V (LM5100)		0.1	**0.2**	mA
		LI = HI = 0V (LM5101)		0.25	**0.4**	
I_{DDO}	V_{DD} Operating Current	f = 500 kHz		1.5	**3**	mA
I_{HB}	Total HB Quiescent Current	LI = HI = 0V		0.06	**0.2**	mA
I_{HBO}	Total HB Operating Current	f = 500 kHz		1.3	**3**	mA
I_{HBS}	HB to V_{SS} Current, Quiescent	$V_{HS} = V_{HB} = 100V$		0.05	**10**	µA
I_{HBSO}	HB to V_{SS} Current, Operating	f = 500 kHz		0.08		mA
INPUT PINS						
V_{IL}	Low Level Input Voltage Threshold (LM5100)		**3**	5.0		V
V_{IL}	Low Level Input Voltage Threshold (LM5101)		**0.8**	1.8		V
V_{IH}	High Level Input Voltage Threshold (LM5100)			5.5	**8**	V
V_{IH}	High Level Input Voltage Threshold (LM5101)			1.8	**2.2**	V
V_{IHYS}	Input Voltage Hysteresis (LM5100)			0.5		V
R_I	Input Pulldown Resistance		**100**	200	**500**	kΩ
UNDER VOLTAGE PROTECTION						
V_{DDR}	V_{DD} Rising Threshold		**6.0**	6.9	**7.4**	V
V_{DDH}	V_{DD} Threshold Hysteresis			0.5		V
V_{HBR}	HB Rising Threshold		**5.7**	6.6	**7.1**	V
V_{HBH}	HB Threshold Hysteresis			0.4		V
BOOT STRAP DIODE						
V_{DL}	Low-Current Forward Voltage	$I_{VDD-HB} = 100\ \mu A$		0.6	**0.9**	V
V_{DH}	High-Current Forward Voltage	$I_{VDD-HB} = 100\ mA$		0.85	**1.1**	V
R_D	Dynamic Resistance	$I_{VDD-HB} = 100\ mA$		0.8	**1.5**	Ω
LO GATE DRIVER						
V_{OLL}	Low-Level Output Voltage	$I_{LO} = 100\ mA$		0.23	**0.4**	V
V_{OHL}	High-Level Output Voltage	$I_{LO} = -100\ mA$, $V_{OHL} = V_{DD}-V_{LO}$		0.35	**0.55**	V
I_{OHL}	Peak Pullup Current	$V_{LO} = 0V$		1.6		A
I_{OLL}	Peak Pulldown Current	$V_{LO} = 12V$		1.8		A
HO GATE DRIVER						
V_{OLH}	Low-Level Output Voltage	$I_{HO} = 100\ mA$		0.23	**0.4**	V

Figure C-6:



Features

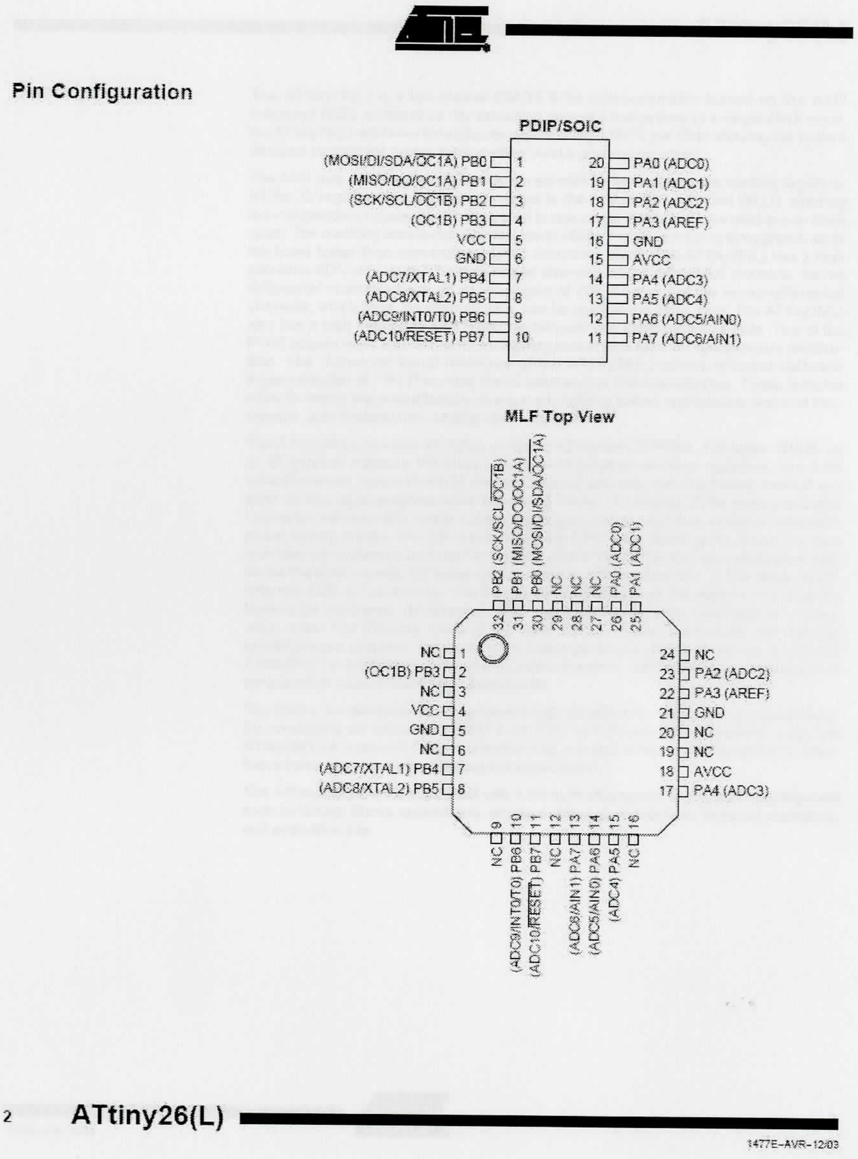
- High-performance, Low-power *AVR*® 8-bit Microcontroller
- RISC Architecture
  - 118 Powerful Instructions – Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 16 MIPS Throughput at 16 MHz
- Data and Non-volatile Program Memory
  - 2K Bytes of In-System Programmable Program Memory Flash
    Endurance: 10,000 Write/Erase Cycles
  - 128 Bytes of In-System Programmable EEPROM
    Endurance: 100,000 Write/Erase Cycles
  - 128 Bytes Internal SRAM
  - Programming Lock for Flash Program and EEPROM Data Security
- Peripheral Features
  - 8-bit Timer/Counter with Separate Prescaler
  - 8-bit High-speed Timer with Separate Prescaler
    2 High Frequency PWM Outputs with Separate Output Compare Registers
    Non-overlapping Inverted PWM Output Pins
  - Universal Serial Interface with Start Condition Detector
  - 10-bit ADC
    11 Single Ended Channels
    8 Differential ADC Channels
    7 Differential ADC Channel Pairs with Programmable Gain (1x, 20x)
  - On-chip Analog Comparator
  - External Interrupt
  - Pin Change Interrupt on 11 Pins
  - Programmable Watchdog Timer with Separate On-chip Oscillator
- Special Microcontroller Features
  - Low Power Idle, Noise Reduction, and Power-down Modes
  - Power-on Reset and Programmable Brown-out Detection
  - External and Internal Interrupt Sources
  - In-System Programmable via SPI Port
  - Internal Calibrated RC Oscillator
- I/O and Packages
  - 20-lead PDIP/SOIC: 16 Programmable I/O Lines
  - 32-lead MLF: 16 programmable I/O Lines
- Operating Voltages
  - 2.7V - 5.5V for ATtiny26L
  - 4.5V - 5.5V for ATtiny26
- Speed Grades
  - 0 - 8 MHz for ATtiny26L
  - 0 - 16 MHz for ATtiny26
- Power Consumption at 1 MHz, 3V and 25°C for ATtiny26L
  - Active 16 MHz, 5V and 25°C: Typ 15 mA
  - Active 1 MHz, 3V and 25°C: 0.70 mA
  - Idle Mode 1 MHz, 3V and 25°C: 0.18 mA
  - Power-down Mode: < 1 µA

8-bit AVR® Microcontroller with 2K Bytes Flash

ATtiny26
ATtiny26L

Rev. 1477E–AVR–12/03

Figure C-7:

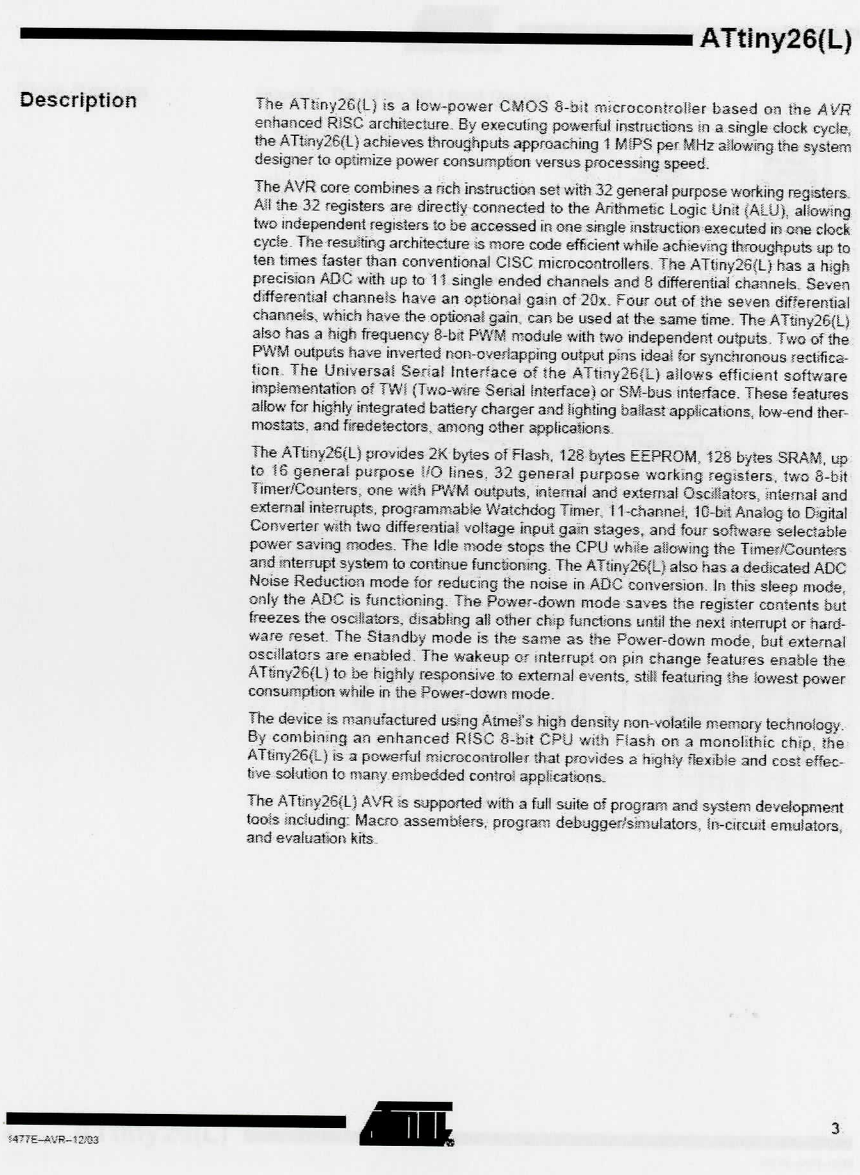


Pin Configuration

2 **ATtiny26(L)**

1477E–AVR–12/03

Figure C-8:



ATtiny26(L)

Description

The ATtiny26(L) is a low-power CMOS 8-bit microcontroller based on the *AVR* enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATtiny26(L) achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed.

The AVR core combines a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture is more code efficient while achieving throughputs up to ten times faster than conventional CISC microcontrollers. The ATtiny26(L) has a high precision ADC with up to 11 single ended channels and 8 differential channels. Seven differential channels have an optional gain of 20x. Four out of the seven differential channels, which have the optional gain, can be used at the same time. The ATtiny26(L) also has a high frequency 8-bit PWM module with two independent outputs. Two of the PWM outputs have inverted non-overlapping output pins ideal for synchronous rectification. The Universal Serial Interface of the ATtiny26(L) allows efficient software implementation of TWI (Two-wire Serial Interface) or SM-bus interface. These features allow for highly integrated battery charger and lighting ballast applications, low-end thermostats, and firedetectors, among other applications.

The ATtiny26(L) provides 2K bytes of Flash, 128 bytes EEPROM, 128 bytes SRAM, up to 16 general purpose I/O lines, 32 general purpose working registers, two 8-bit Timer/Counters, one with PWM outputs, internal and external Oscillators, internal and external interrupts, programmable Watchdog Timer, 11-channel, 10-bit Analog to Digital Converter with two differential voltage input gain stages, and four software selectable power saving modes. The Idle mode stops the CPU while allowing the Timer/Counters and interrupt system to continue functioning. The ATtiny26(L) also has a dedicated ADC Noise Reduction mode for reducing the noise in ADC conversion. In this sleep mode, only the ADC is functioning. The Power-down mode saves the register contents but freezes the oscillators, disabling all other chip functions until the next interrupt or hardware reset. The Standby mode is the same as the Power-down mode, but external oscillators are enabled. The wakeup or interrupt on pin change features enable the ATtiny26(L) to be highly responsive to external events, still featuring the lowest power consumption while in the Power-down mode.

The device is manufactured using Atmel's high density non-volatile memory technology. By combining an enhanced RISC 8-bit CPU with Flash on a monolithic chip, the ATtiny26(L) is a powerful microcontroller that provides a highly flexible and cost effective solution to many embedded control applications.

The ATtiny26(L) AVR is supported with a full suite of program and system development tools including: Macro assemblers, program debugger/simulators, In-circuit emulators, and evaluation kits.

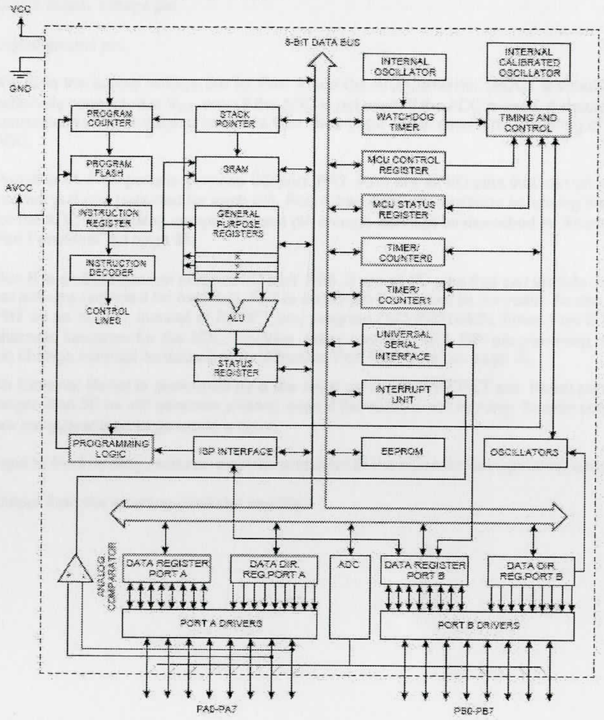
1477E–AVR–12/03

3

Figure C-9:

Block Diagram

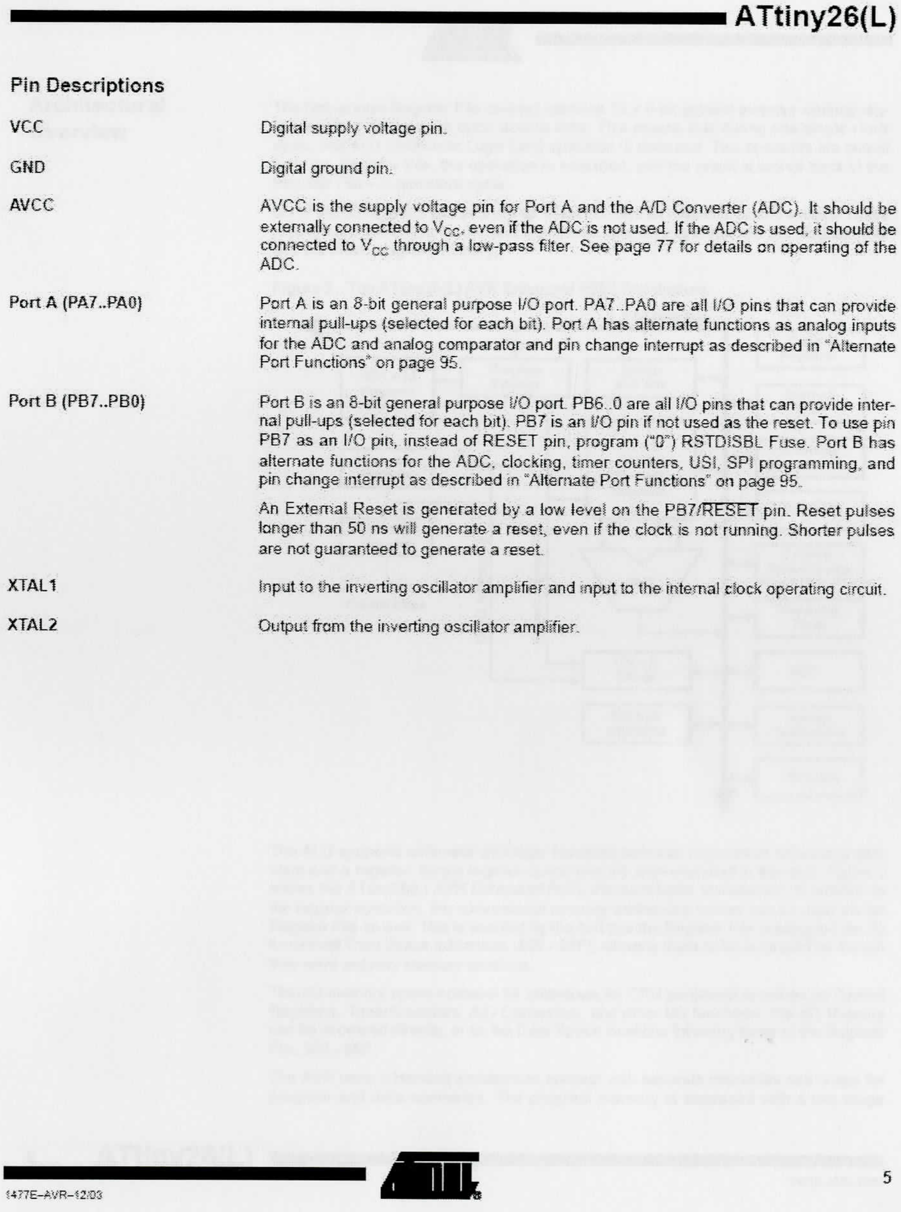
Figure 1. The ATtiny26(L) Block Diagram



4 **ATtiny26(L)**

1477E–AVR–12/03

Figure C-10:



ATtiny26(L)

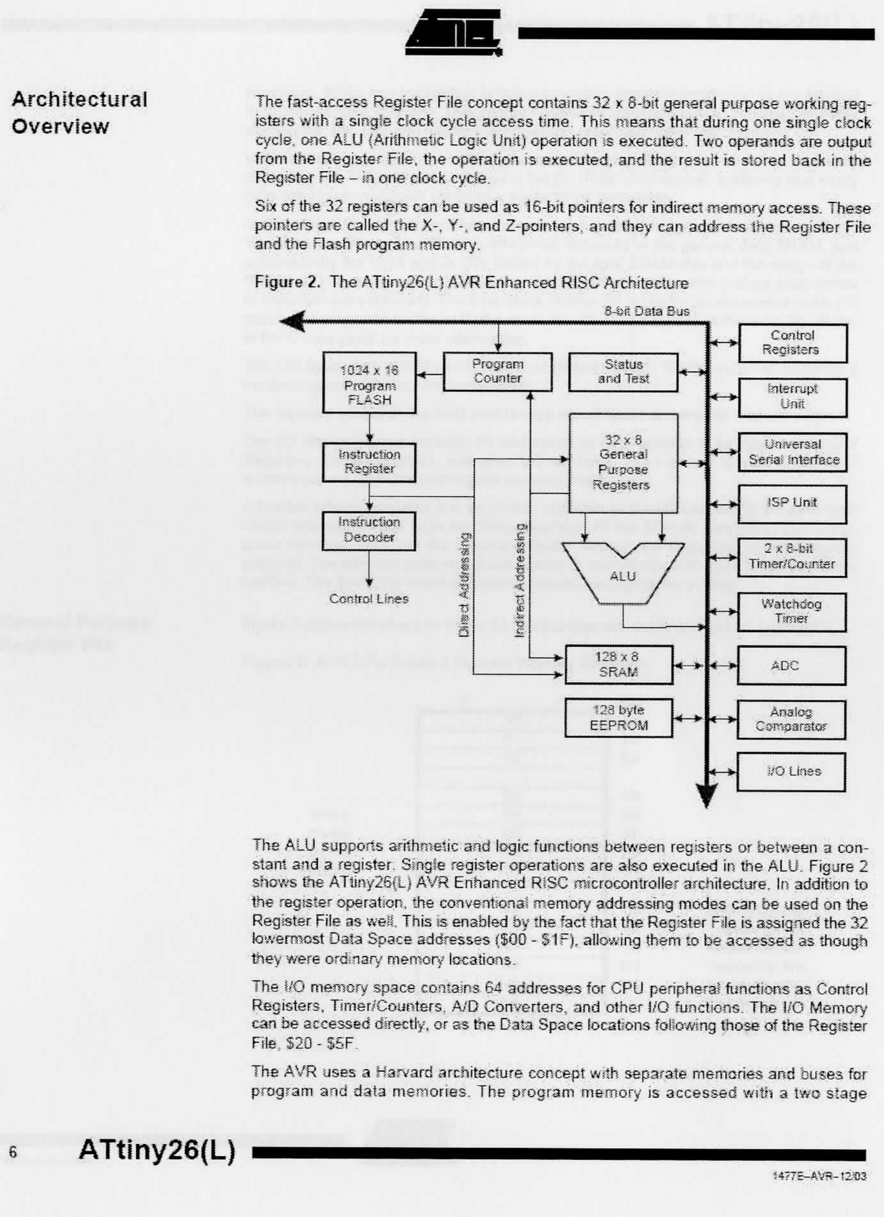
Pin Descriptions

VCC	Digital supply voltage pin.
GND	Digital ground pin.
AVCC	AVCC is the supply voltage pin for Port A and the A/D Converter (ADC). It should be externally connected to V_{CC}, even if the ADC is not used. If the ADC is used, it should be connected to V_{CC} through a low-pass filter. See page 77 for details on operating of the ADC.
Port A (PA7..PA0)	Port A is an 8-bit general purpose I/O port. PA7..PA0 are all I/O pins that can provide internal pull-ups (selected for each bit). Port A has alternate functions as analog inputs for the ADC and analog comparator and pin change interrupt as described in "Alternate Port Functions" on page 95.
Port B (PB7..PB0)	Port B is an 8-bit general purpose I/O port. PB6..0 are all I/O pins that can provide internal pull-ups (selected for each bit). PB7 is an I/O pin if not used as the reset. To use pin PB7 as an I/O pin, instead of RESET pin, program ("0") RSTDISBL Fuse. Port B has alternate functions for the ADC, clocking, timer counters, USI, SPI programming, and pin change interrupt as described in "Alternate Port Functions" on page 95. An External Reset is generated by a low level on the PB7/$\overline{\text{RESET}}$ pin. Reset pulses longer than 50 ns will generate a reset, even if the clock is not running. Shorter pulses are not guaranteed to generate a reset.
XTAL1	Input to the inverting oscillator amplifier and input to the internal clock operating circuit.
XTAL2	Output from the inverting oscillator amplifier.

1477E–AVR–12/03

5

Figure C-11:



Architectural Overview

The fast-access Register File concept contains 32 x 8-bit general purpose working registers with a single clock cycle access time. This means that during one single clock cycle, one ALU (Arithmetic Logic Unit) operation is executed. Two operands are output from the Register File, the operation is executed, and the result is stored back in the Register File – in one clock cycle.

Six of the 32 registers can be used as 16-bit pointers for indirect memory access. These pointers are called the X-, Y-, and Z-pointers, and they can address the Register File and the Flash program memory.

Figure 2. The ATtiny26(L) AVR Enhanced RISC Architecture

The ALU supports arithmetic and logic functions between registers or between a constant and a register. Single register operations are also executed in the ALU. Figure 2 shows the ATtiny26(L) AVR Enhanced RISC microcontroller architecture. In addition to the register operation, the conventional memory addressing modes can be used on the Register File as well. This is enabled by the fact that the Register File is assigned the 32 lowermost Data Space addresses ($00 - $1F), allowing them to be accessed as though they were ordinary memory locations.

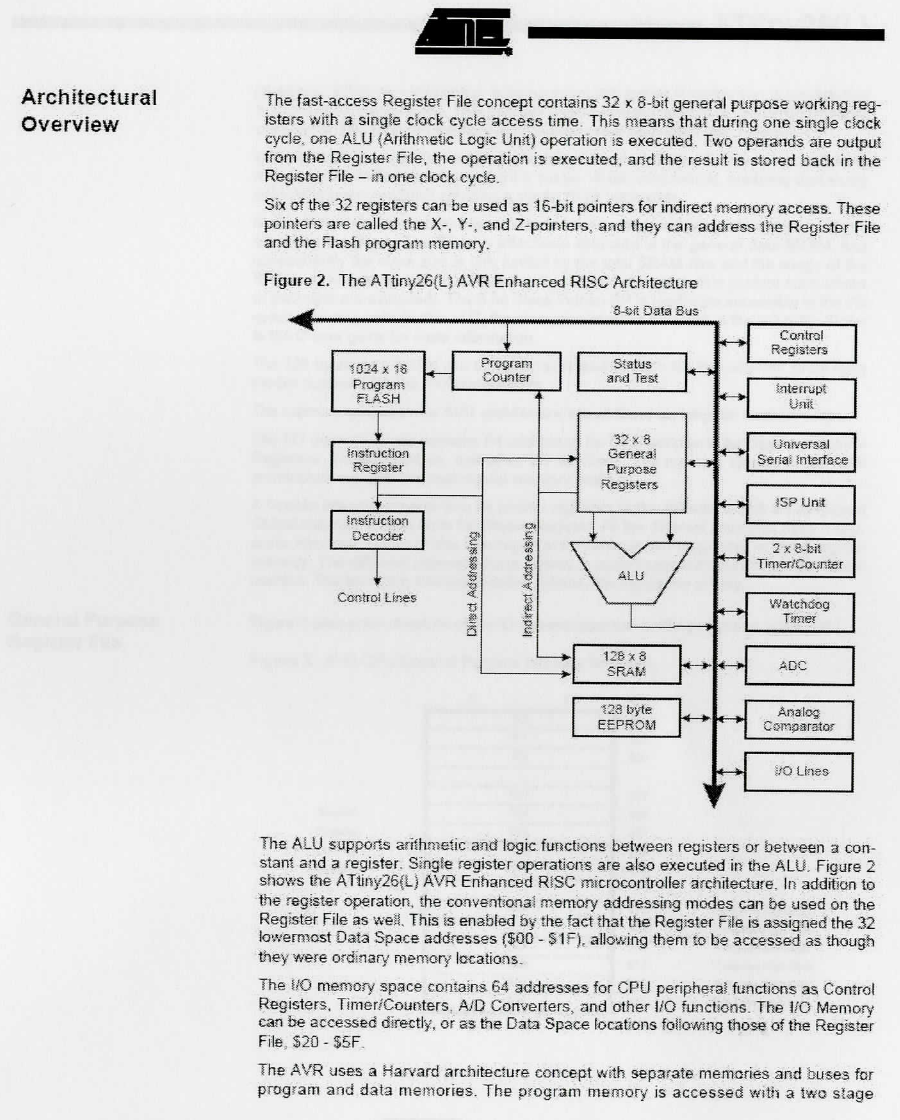
The I/O memory space contains 64 addresses for CPU peripheral functions as Control Registers, Timer/Counters, A/D Converters, and other I/O functions. The I/O Memory can be accessed directly, or as the Data Space locations following those of the Register File, $20 - $5F.

The AVR uses a Harvard architecture concept with separate memories and buses for program and data memories. The program memory is accessed with a two stage

6 **ATtiny26(L)**

1477E–AVR–12/03

Figure C-12:



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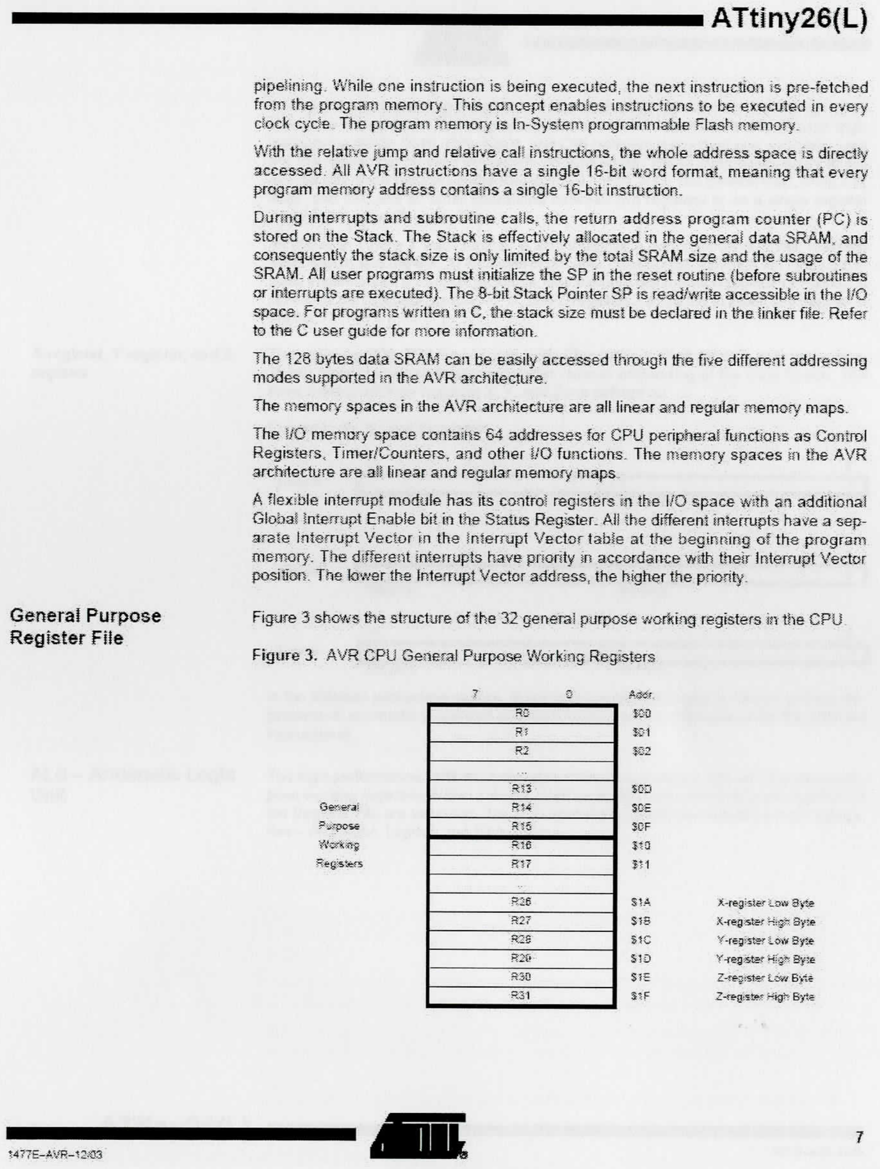
6 **ATtiny26(L)**

1477E–AVR–12/03

Figure C-12:



ATtiny26(L)

pipelining. While one instruction is being executed, the next instruction is pre-fetched from the program memory. This concept enables instructions to be executed in every clock cycle. The program memory is In-System programmable Flash memory.

With the relative jump and relative call instructions, the whole address space is directly accessed. All AVR instructions have a single 16-bit word format, meaning that every program memory address contains a single 16-bit instruction.

During interrupts and subroutine calls, the return address program counter (PC) is stored on the Stack. The Stack is effectively allocated in the general data SRAM, and consequently the stack size is only limited by the total SRAM size and the usage of the SRAM. All user programs must initialize the SP in the reset routine (before subroutines or interrupts are executed). The 8-bit Stack Pointer SP is read/write accessible in the I/O space. For programs written in C, the stack size must be declared in the linker file. Refer to the C user guide for more information.

The 128 bytes data SRAM can be easily accessed through the five different addressing modes supported in the AVR architecture.

The memory spaces in the AVR architecture are all linear and regular memory maps.

The I/O memory space contains 64 addresses for CPU peripheral functions as Control Registers, Timer/Counters, and other I/O functions. The memory spaces in the AVR architecture are all linear and regular memory maps.

A flexible interrupt module has its control registers in the I/O space with an additional Global Interrupt Enable bit in the Status Register. All the different interrupts have a separate Interrupt Vector in the Interrupt Vector table at the beginning of the program memory. The different interrupts have priority in accordance with their Interrupt Vector position. The lower the Interrupt Vector address, the higher the priority.

General Purpose Register File

Figure 3 shows the structure of the 32 general purpose working registers in the CPU.

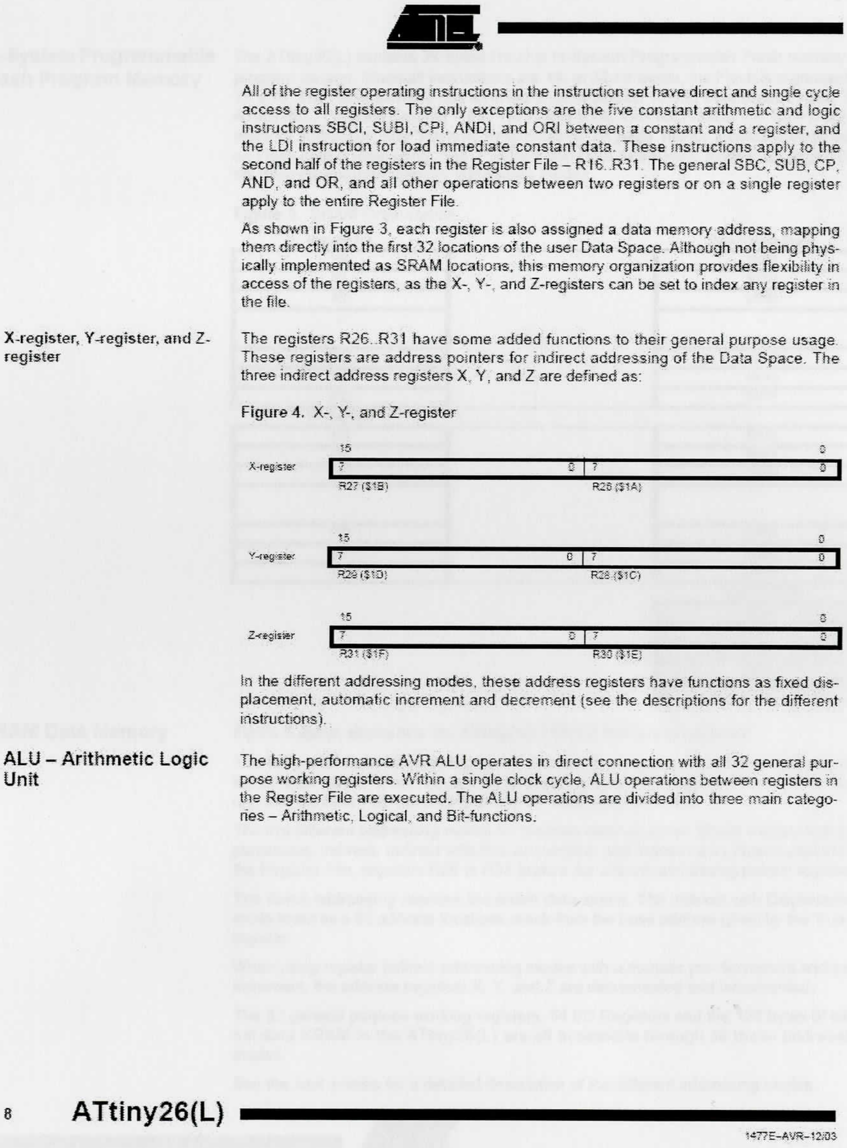
Figure 3. AVR CPU General Purpose Working Registers

	7 0	Addr.	
	R0	$00	
	R1	$01	
	R2	$02	
	...		
	R13	$0D	
General	R14	$0E	
Purpose	R15	$0F	
Working	R16	$10	
Registers	R17	$11	
	...		
	R26	$1A	X-register Low Byte
	R27	$1B	X-register High Byte
	R28	$1C	Y-register Low Byte
	R29	$1D	Y-register High Byte
	R30	$1E	Z-register Low Byte
	R31	$1F	Z-register High Byte

1477E–AVR–12/03

7

Figure C-13:



All of the register operating instructions in the instruction set have direct and single cycle access to all registers. The only exceptions are the five constant arithmetic and logic instructions SBCI, SUBI, CPI, ANDI, and ORI between a constant and a register, and the LDI instruction for load immediate constant data. These instructions apply to the second half of the registers in the Register File – R16..R31. The general SBC, SUB, CP, AND, and OR, and all other operations between two registers or on a single register apply to the entire Register File.

As shown in Figure 3, each register is also assigned a data memory address, mapping them directly into the first 32 locations of the user Data Space. Although not being physically implemented as SRAM locations, this memory organization provides flexibility in access of the registers, as the X-, Y-, and Z-registers can be set to index any register in the file.

X-register, Y-register, and Z-register

The registers R26..R31 have some added functions to their general purpose usage. These registers are address pointers for indirect addressing of the Data Space. The three indirect address registers X, Y, and Z are defined as:

Figure 4. X-, Y-, and Z-register

In the different addressing modes, these address registers have functions as fixed displacement, automatic increment and decrement (see the descriptions for the different instructions).

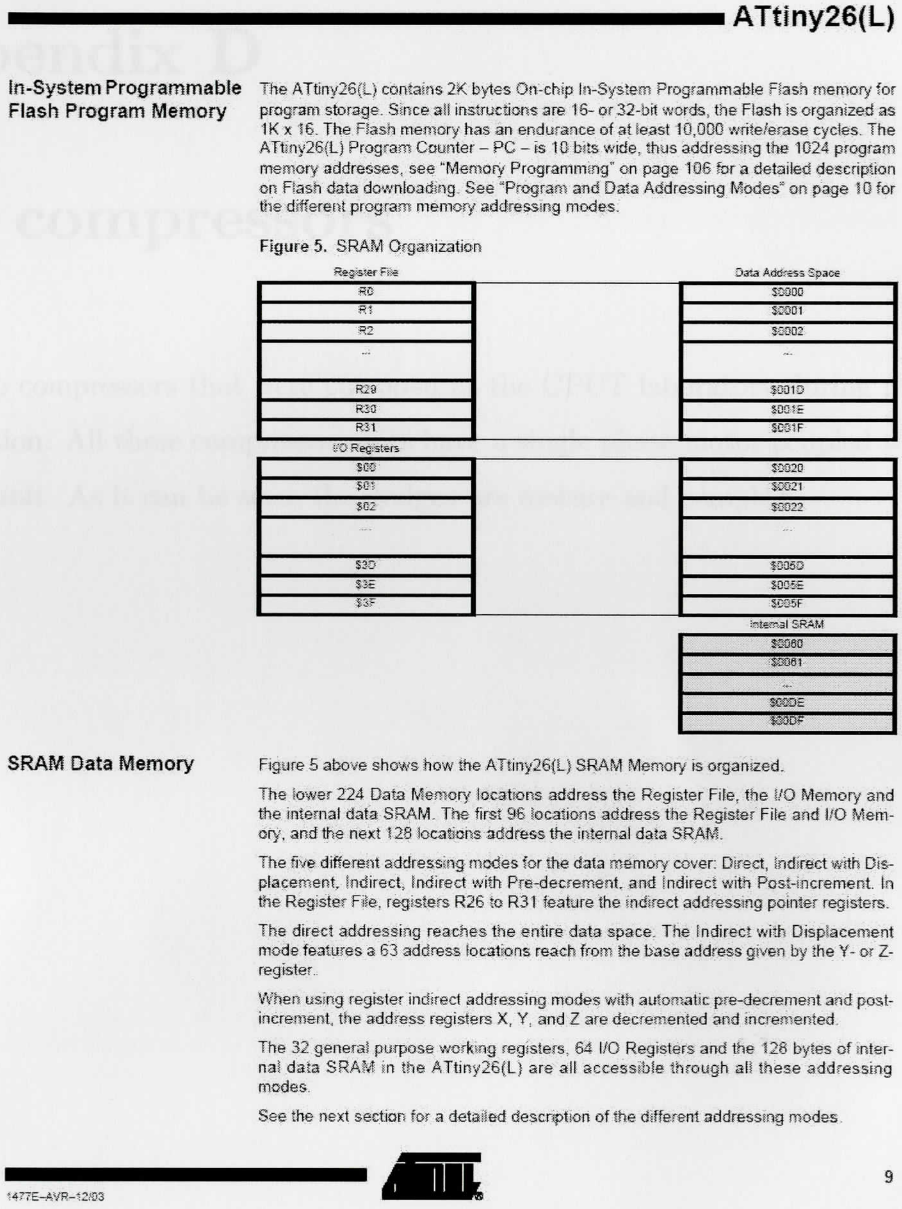
ALU – Arithmetic Logic Unit

The high-performance AVR ALU operates in direct connection with all 32 general purpose working registers. Within a single clock cycle, ALU operations between registers in the Register File are executed. The ALU operations are divided into three main categories – Arithmetic, Logical, and Bit-functions.

8 **ATtiny26(L)**

1477E–AVR–12/03

Figure C-14:



ATtiny26(L)

In-System Programmable Flash Program Memory

The ATtiny26(L) contains 2K bytes On-chip In-System Programmable Flash memory for program storage. Since all instructions are 16- or 32-bit words, the Flash is organized as 1K x 16. The Flash memory has an endurance of at least 10,000 write/erase cycles. The ATtiny26(L) Program Counter – PC – is 10 bits wide, thus addressing the 1024 program memory addresses, see "Memory Programming" on page 106 for a detailed description on Flash data downloading. See "Program and Data Addressing Modes" on page 10 for the different program memory addressing modes.

Figure 5. SRAM Organization

Register File	Data Address Space
R0	$0000
R1	$0001
R2	$0002
...	...
R29	$001D
R30	$001E
R31	$001F
I/O Registers	
$00	$0020
$01	$0021
$02	$0022
...	...
$3D	$005D
$3E	$005E
$3F	$005F
	Internal SRAM
	$0060
	$0061
	...
	$00DE
	$00DF

SRAM Data Memory

Figure 5 above shows how the ATtiny26(L) SRAM Memory is organized.

The lower 224 Data Memory locations address the Register File, the I/O Memory and the internal data SRAM. The first 96 locations address the Register File and I/O Memory, and the next 128 locations address the internal data SRAM.

The five different addressing modes for the data memory cover: Direct, Indirect with Displacement, Indirect, Indirect with Pre-decrement, and Indirect with Post-increment. In the Register File, registers R26 to R31 feature the indirect addressing pointer registers.

The direct addressing reaches the entire data space. The Indirect with Displacement mode features a 63 address locations reach from the base address given by the Y- or Z-register.

When using register indirect addressing modes with automatic pre-decrement and post-increment, the address registers X, Y, and Z are decremented and incremented.

The 32 general purpose working registers, 64 I/O Registers and the 128 bytes of internal data SRAM in the ATtiny26(L) are all accessible through all these addressing modes.

See the next section for a detailed description of the different addressing modes.

9

1477E–AVR–12/03

Figure C-15:

Appendix D

Old compressors

The scrap compressors that were cut open at the CPUT laboratory during preliminary investigation. All these compressor units have a single phase motor coupled to the compression unit. As it can be seen, the designs are mature and complex.

Table D.1: A and B shows the scotch yoke type of reciprocating compressor, C. Valve parts for scotch yoke and D. half cut open compressor enclosure

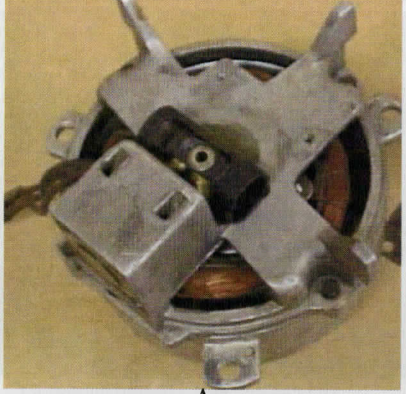
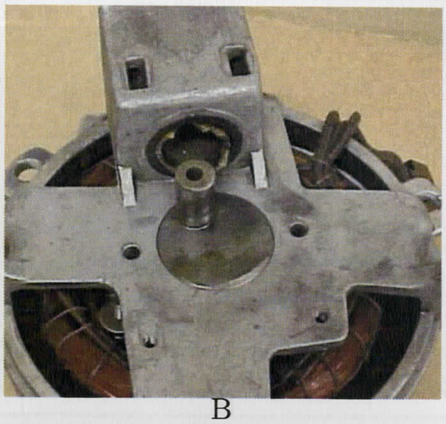
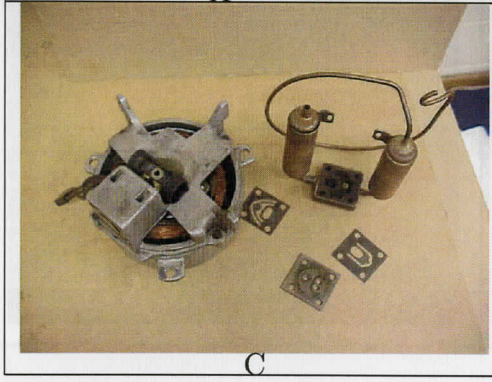
 A	 B
 C	 D

Table D.2: A. Reciprocating piston compressor, B. rotor of the motor driving the compressor, C.Valve parts and D.Compressor enclosure

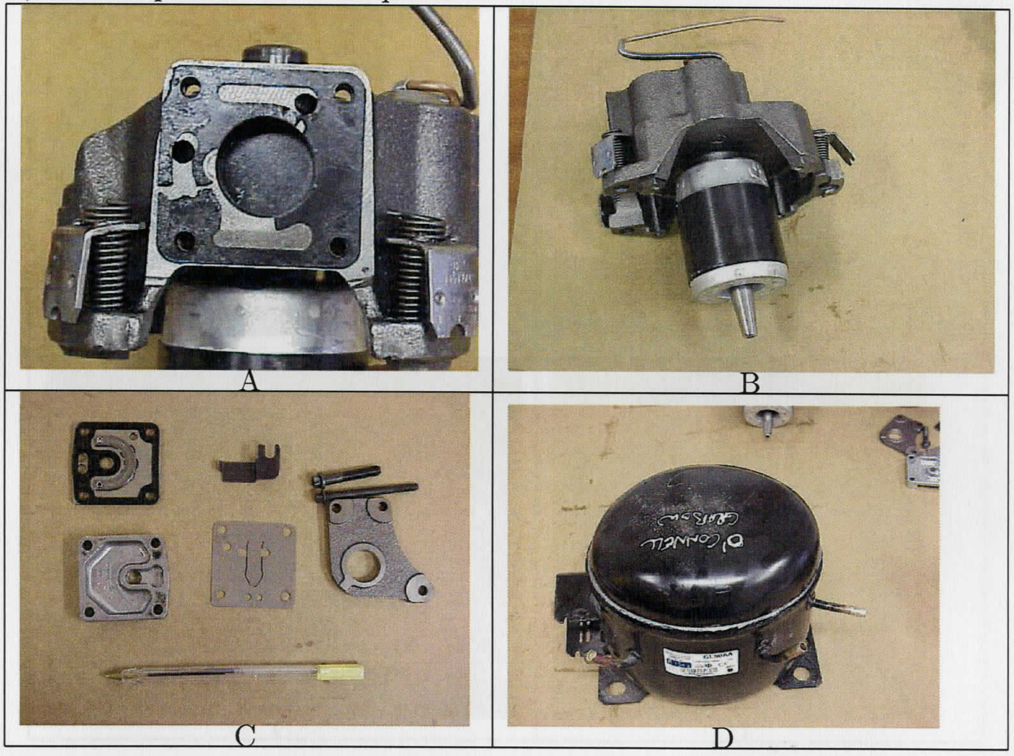
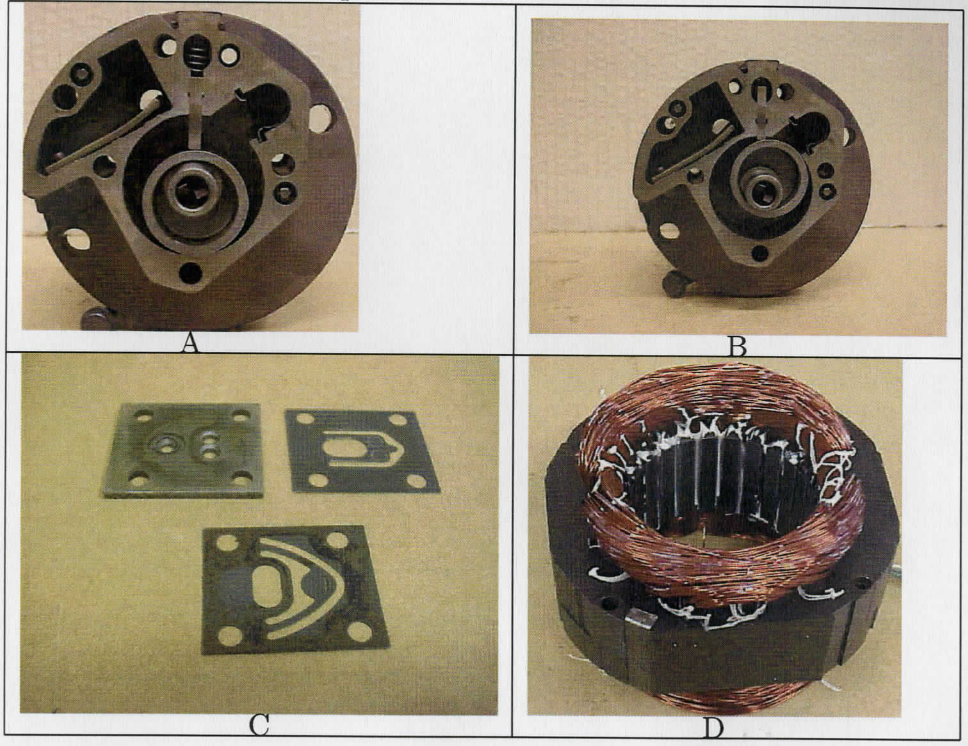


Table D.3: A and B. Rolling piston type of compressor, C. Valve parts and D. the stator of the motor that drives the compressor



A

B

C

D