LINEAR MOTOR FOR AIR VAPOR COMPRESSOR

By

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FINAL PROJECT REPORT

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Electrical & Electronics Engineering Programme

Universiti Teknologi PETRONAS

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Approval by:

____

Dr. Taib Bin Ibrahim

UNIVERSITI TEKNOLOGI PETRONAS

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SEPTEMBER 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified source or persons.

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INSYIRAH BINTI SALIM

ABSTRACT

This paper describes the modeling of linear motor compressor for use in household refrigerator compressor system. Literature review has been conducted for various types of linear motor technologies such as linear synchronous motor, linear induction motor, linear dc motor and also linear permanent magnet motor. Three proposed designs has been proposed which are tubular slotless linear motor using rectangular/trapezoidal permanent magnet with the magnet arrangement separately with mild steel and tubular slotless linear motor with rectangular permanent magnet. The designs are proposed due to force capability, simplicity and cost-effectiveness. Type of permanent magnet also will be taken into consideration. The characteristic and other element of the motor will be simulated using ANSYS software.

The results in terms of air gap flux density and moving force have been presented. The most suitable design is chosen based on the higher average value of magnetic flux and force. In addition, this project is mainly focused on the selection of the design from the three proposed design that have been proposed. In future work, the selected design then can undergo design optimization to prove that the design can increase the efficiency of the compressor and thus reduce the power consumption.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter involves the background study and main problem that leads to the idea of designing and modeling of linear permanent magnet motor for air vapor compressor that is to be applied into the house refrigerator system. The research has been conducted to review the background and the main problem of the conventional compressor.

1.2 Background of Study

The recent global awareness of the environmental protection raised great attention for energy saving of the household refrigerator. In most homes the refrigerator is the second-largest user of electricity (13.7%), right after the air conditioner (16%) [1]. Nowadays, most of this appliance is powered by crank driven compressors which consume most of its electricity consumptions. In year 2010, world energy consumption has increase over 5%. This strong increase is the result of two converging trends. Industrialized countries, which experienced sharp decreases in energy demand in 2009, recovered firmly in 2010, almost coming back to historical trends. Oil, gas, coal, and electricity markets followed the same trend. Moreover, China and India, which showed no signs of slowing down in 2009, continued their intense demand for all forms of energy [2].

Efficiency of the refrigerator compressor system significantly influences the use of electrical energy [9]. Since conventional crank driven compressor had many difficulties to increase the efficiency, the new kind of compressor had been paid more attention by the compressor manufacture. The direct-driven compressor is one of these kinds which can increase the efficiency of the compressor. It does not produce any side load on the sliding bearing [3]. This direct-driven compressor can get better efficiency by reducing the friction loss. Furthermore, the stroke of the direct-driven in the free linear compressor can be adjusted to modulate the compressor cooling capacity for better system. Figure 1 shows the schematic of conventional refrigerator compressor.

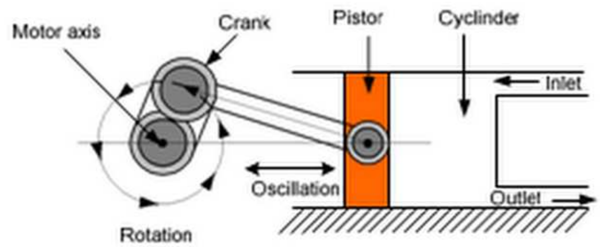


Figure 1: Schematic of Conventional Refrigerator Compressor [9]

Figure 2 shows the role of compressor in the refrigerator cycle. To control the circulation of the refrigerant, it works as a pump and then the pressure of the refrigerant will increase and raised its temperature. The compressor also draws vapor away from the evaporator to maintain a lower pressure and lower temperature before sending it to the condenser [4]. The condenser then removes the heat and the temperature is making sure below the boiling point before entering the expansion valve. The reducing pressure in the expansion valve causes the liquid to boil and evaporated and the evaporation process take place in the evaporator thus completes the cycle [5].

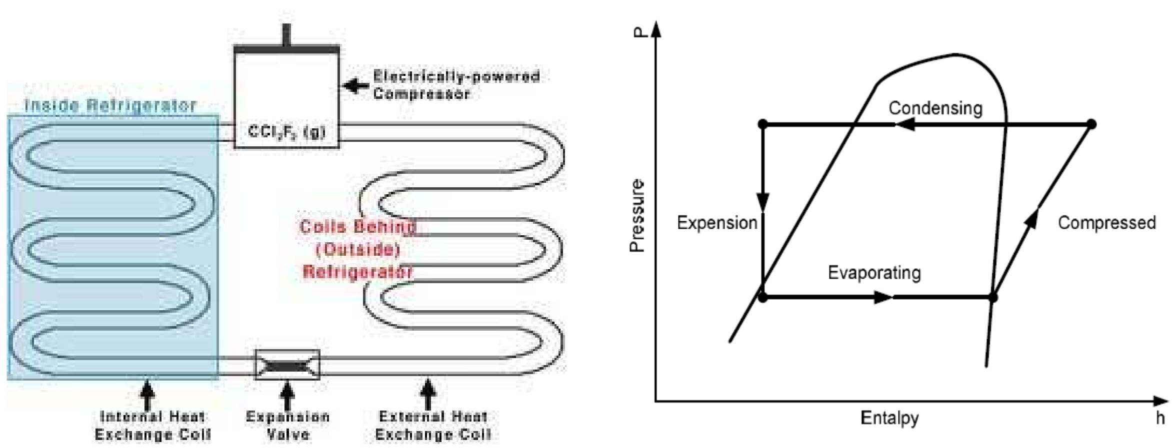


Figure 2: Refrigeration Cycle [3]

On the other hand, refrigerators have recently been introduced which employ a direct-drive linear motor driven compressor. Such a compressor eliminates the need for rotary-to-linear motion conversion cranks which reduces the complexity, volume and power loss due to mechanical friction. A direct-drive linear compressor is also more robust, quieter, more reliable and less costly, and improves the dynamic performance [6]. Figure 3 shows the scale of the reduction in energy consumption that achieves by the direct-drive linear compressor compare to a rotary or crank driven compressor and by implementing variable cooling capacity operation.

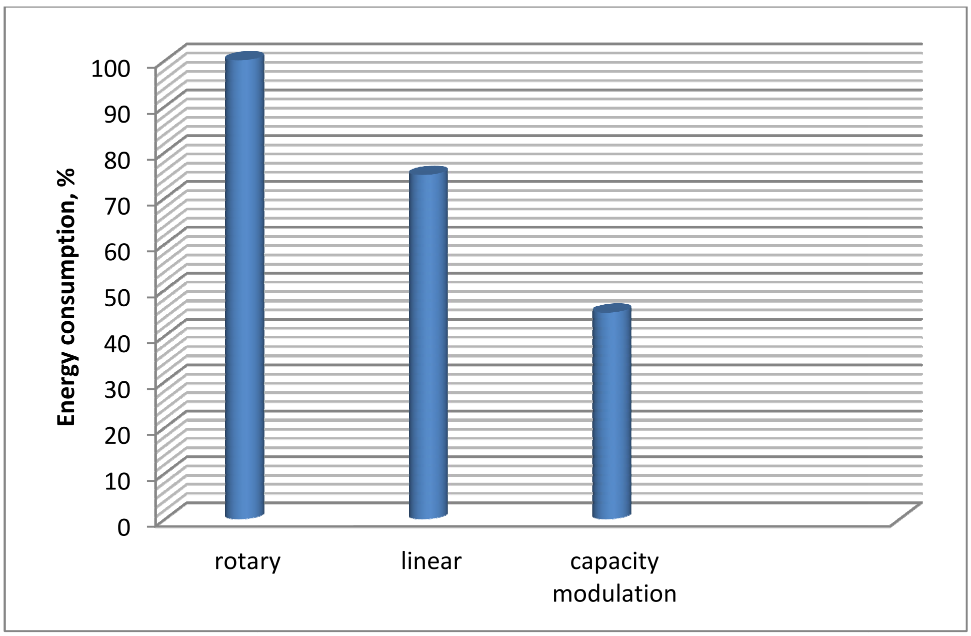


Figure 3: Energy Consumption of Different Technologies [9]

Figure 4 shows the schematic diagram of a direct-drive linear compressor. As will be seen, the diagram eliminates the crank shaft and the system may produce higher efficiency.

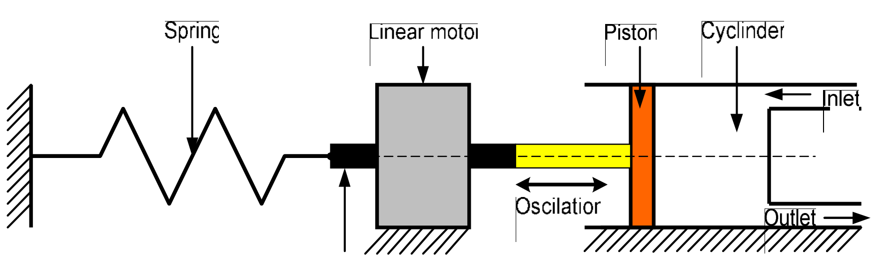


Figure 4: Schematic Diagram of Direct-drive Linear Compressor [9]

In order to get a maximum efficiency, maximum refrigerant gas flow, the electrical supply frequency to the linear motor should match with the mechanical resonant frequency of the moving mass. Therefore, the design of the linear motor will have an important influence on the operation of a direct-drive compressor. In this proposal, the motor topologies and present comprehensive analysis and performance prediction has been assess.

1.3 Problem Statement

Refrigerator is one of the most important appliances for daily life. However, there are several impacts mostly to the environment due to the usage of the refrigerator. Refrigerator contains ozone depleting and global warning substance such as chlorofluorocarbons (CFCs) in their insulation foam which contributes to the global warming and ozone layer depletion. This problem is due to inefficient of the refrigerator system. The efficiency of the refrigerator system is highly based on its compressor [26].

The most technical problem using conventional refrigerator compressor is that the friction of the crank-drive piston movement which use the concept of rotary motor. This friction makes the performance of the refrigerator low. Also, the side force between the piston and cylinder is high thus lower the smoother of the motor.

In order to improve the performance of the compressor, it must eliminates the need for rotary-to-linear motion conversion crank which can reduce the complexity, volume and power loss due to mechanical friction. This will produce a compressor with robust, high performance and quieter design. Therefore, this paper is conduct to develop a linear motor for air vapor compressor for refrigerator system that can replace the conventional compressor system.

1.4 Objectives

The objective of this project is to develop a linear motor compressor for use in household refrigerator system. The other objectives are:

a) To conduct literature review of linear motor topologies
b) To propose several design in order to satisfy the linear motor for air vapor compressor system characteristics.
c) To choose the most suitable design by getting the result using ANSYS software.

1.5 Scope of Study

This paper is about the development of linear motor for air vapor compressor that use in the household refrigerator system. In this paper there are 5 chapters. Chapter 1 will talk about the background study and main problem of the refrigerator compressor.

Chapter 2, the author has studied several literature reviews about linear motor and its application. The source of the literature review is from internet, journal, and reference book. However, the literature review mostly comes from Institute of Electrical and Electronic Engineer (IEEE) source.

Chapter 3 then will talk about methodologies that have been used throughout the project. The design is simulate using ANSYS software to get the result.

Chapter 4 is about the result and discussion for the project. In this chapter, the types of all linear motors have been compared in order to choose the best and suitable linear motor machine for this project.

Chapter 5 is the conclusion for the project which most suitable design has been chosen and the future work that can be done.

1.6 Conclusion

Due to great attention for energy saving of the household refrigerator, new invention of linear permanent magnet motor for air vapor compressor has been taken into consideration. This project will increase the performance of the compressor thus increase the efficiency of the refrigerator. In order to proceed with this project, a few methodologies that need to be executed for instance, study on various topologies of linear machines that is suitable to be applied into this project. Also, to design and improve from the initial design in order to produce more efficient machine, to obtain the optimum number of flux.

CHAPTER 2

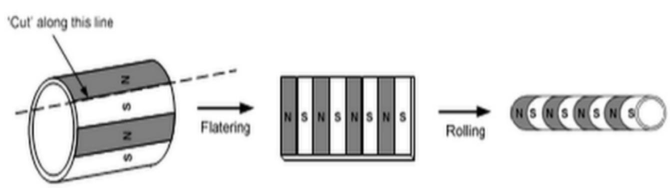
LITERATURE REVIEW

2.1 Introduction

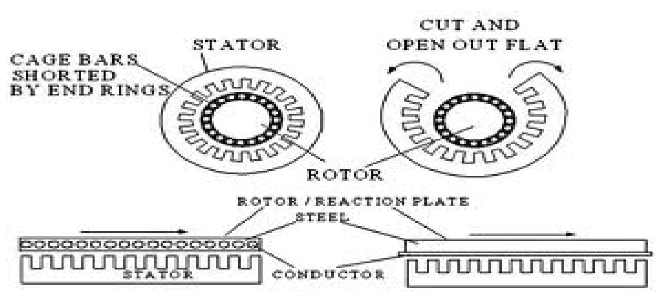
This chapter involves the literature review on the various topologies of the linear machine for instances linear synchronous machine, linear DC machine, linear induction machine and last but not least is linear permanent magnet machine. A suitable linear machine will be chosen to be applied into this project. Three new design of the chosen linear motor will be proposed in order to meet the criteria needed for this project.

2.2 Basic Theory of Linear Motor

Nowadays, linear motion application is more demanding than before. This is due to faster throughout, more exact positioning, longer life, less maintenance and also fewer moving parts. The linear motor concept can be explained in simple way as illustrate in Figure 5. Take a conventional rotary servo motor and unwrap it. Then, the stator is now a forcer and the rotor becomes coil or magnet rail. With this design, the load is connected directly to the motor. Direct linear motion is achieved without any rotary to linear transmission devices [7].



a) Permanent Magnet [9]



b) Induction Motor [7]

Figure 5: Development of linear induction and permanent magnet motors from rotary motors [9]

2.3 Linear Machine Topologies

Over a century ago, the linear motor belongs to special group of electrical machine that convert electric energy to mechanical energy, in the form of movement. This machine type can substitute the system that uses electric rotational motor with planetary gears and lead screw transmission, or hybrid mechanism like hydraulic actuators [10]. There are four linear machine technologies which can be considered in designing the linear compressor motor for refrigerator, they are:

a) Linear synchronous machine
b) Linear DC machine
c) Linear induction machine
d) Linear permanent magnet brushless machines

2.3.1 Linear Synchronous Machine

Linear synchronous motor (LSM) has been extensively researched since early 1970's but only recently has it been used for significant commercial applications. This is due to improvements and cost reduction of permanent magnet, power electronics, microprocessor, and computer aided design tools. Moreover, rotary motor using LSM design technique can offer superior performance to conventional synchronous motor [11]. Following are the features that are common for the LSM than for its rotary counterpart:

i) The air-gap between primary and secondary is large
ii) There are important end effects.
iii) Full thrust is required at zero speed

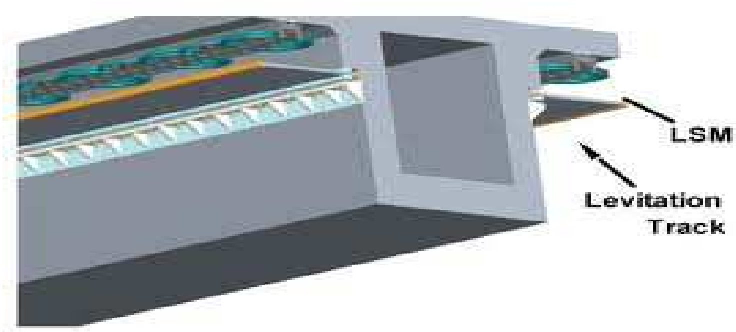


Figure 6: Levitation track using LSM [22]

Advantages of using Linear Synchronous Machine

i) Improve performance on speed and efficiency

ii) Negotiate steeps grades without depending on friction

Disadvantages of using Linear Synchronous Machine

i) Poor performance at low speed

ii) Application is limited due to relative complexity of stator winding

iii) Require three phase power supply

Therefore, the linear synchronous machine is not suitable for compressor design due to complexity of stator winding and low performance at low speed.

2.3.2 Linear DC Machine

In linear DC machine, the motor will run in presence of DC electric power supply. There are two common type of linear DC machine which are brushed and brushless. These two types of motor, it uses internal and external commutation to create an oscillating AC current from the DC source. The linear DC machine is easy and accurate to control of force and position. It is also suitable to be used for long stroke applications. However, there are several drawback of this motor which is [12]:

i) Low performance at low speed

ii) Suffer from brush wear

iii) High maintenance

iv) Make noise during operation

v) Expensive to manufacture

Thus, linear DC machine is not suitable for compressor design due to its DC supply and low performance at low speed.

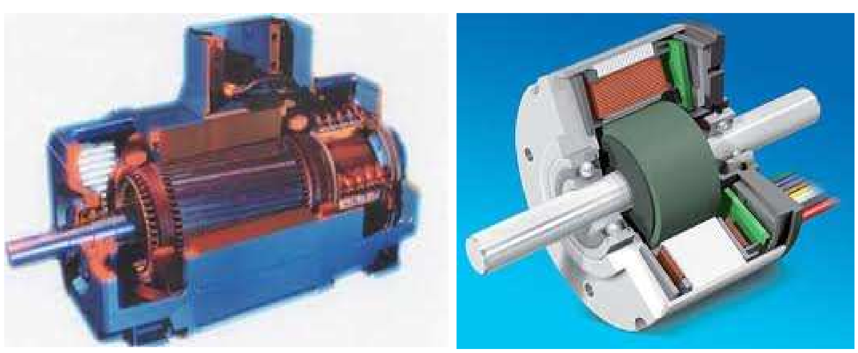


Figure 7: (a) Brushed Linear DC machine (b) Brushless Linear DC machine [23][24]

2.3.3 Linear Induction Machine

Linear induction motor is an AC asynchronous linear motor that works by the same general principles as other induction motor but it has been design to directly produce motion in a straight line. This type of motor mostly used in industrial drive because of their characteristic which is rough and have no brushes. Although this type of motor mostly used in 3-phase system, there are few small appliance that used this type of motor using single phase system. The stator is supply with alternating current (poly-phase current in large machine) and creates a rotating magnetic field which rotates in time with the AC oscillator. The rotor rotates at slower speed than the stator in induction motor which is contrast with synchronous motor [13]. Figure 8 shows the application of the linear induction motor on track unit.

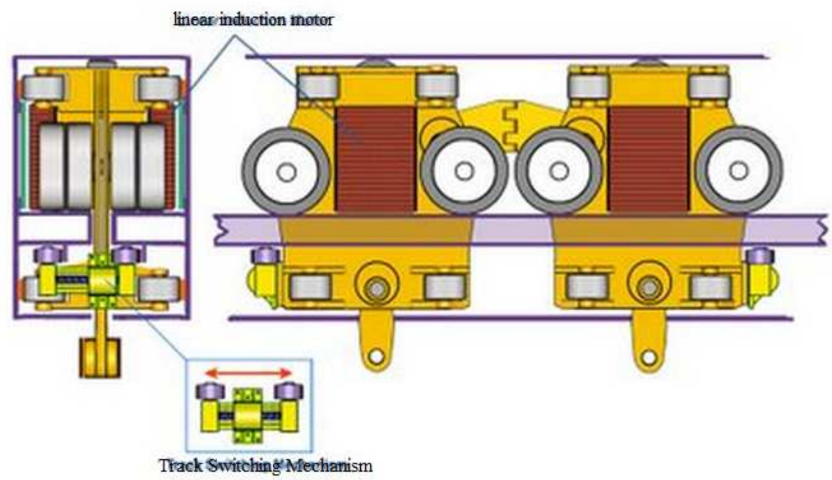


Figure 8: Linear Induction Motor Track Unit [25]

However, there are several drawback of this motor:

i) The motor had poor performance especially at low speed
ii) Complexity of the physical assembly of the stator
iii) The need for a multi-phase winding and a poly-phase supply

The disadvantages of the linear induction machines show that this type of linear motor is not suitable for compressor design because of poor performance at low speed.

2.3.4 Linear Permanent Magnet Motor

Linear permanent magnet machine nowadays are becoming an alternatives solution to rotational motor in many industrial such as transportation and factory automation system. They have many advantages such as quick speed response and high thrust force per volume. They also have simple structure compared with rotational motor [14] [15]. The permanent magnet linear machine as shown in Figure 9 is arguably the simplest configuration. There is no field winding required since the permanent magnet produces the excitation flux for the motor. The moving armature has a short active length whilst the length of the permanent magnet array corresponds to the desired stroke in order to produce optimum thrust force [16].

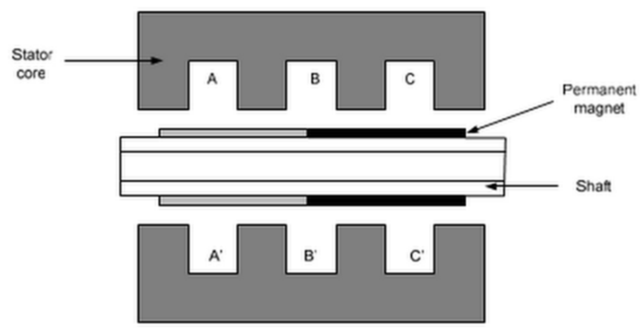


Figure 9: Tubular permanent magnet linear machines [9]

Both planar and tubular topologies can be realized a tubular topology being preferred for a higher thrust force capability. In addition, both slotted and slotless topologies should be considered for improving the thrust force and for reducing the cogging force, respectively. Other topologies which should be considered are iron-cored and air-cored armature configurations, in order to enhance the dynamic capability of a linear motor. As intimated at earlier, a lightweight armature is generally preferred for a vapor linear compressor [17]. In general, however, the permanent magnet linear motors can be classified into three categories:

i. moving-coil

ii. moving-iron

iii. moving-magnet

However, this project is concentrated on slotted and slotless linear permanent magnet motor which is under moving magnet categories.

There are several advantages using moving magnet machine:

a) higher forcer capability

b) higher efficiency

On the other hand, moving coil and moving iron have their own disadvantages.

Disadvantages of moving coil:

a) difficulty in dissipating heat from coil

b) fragility of the connections and flying leads

c) limited access to moving coil

Disadvantages of moving iron:

a) heavy moving mass that can reduce the dynamic capability of the motor

b) relatively low force capability due to low air-gap flux density

2.3.4.1 Slotted permanent magnet linear motor

Moving magnet linear motor has been designed for widely varying applications, such as air compressor, artificial hearts, automotive systems, and robotics [1]. Various possible design variants for both planar and tubular linear motor have been compiled. The linear motor as shown in Figure 10 and Figure 11 encompassing slotted stator, permanent magnet and permanent magnet with ferromagnetic armature and variable constant air-gap design.

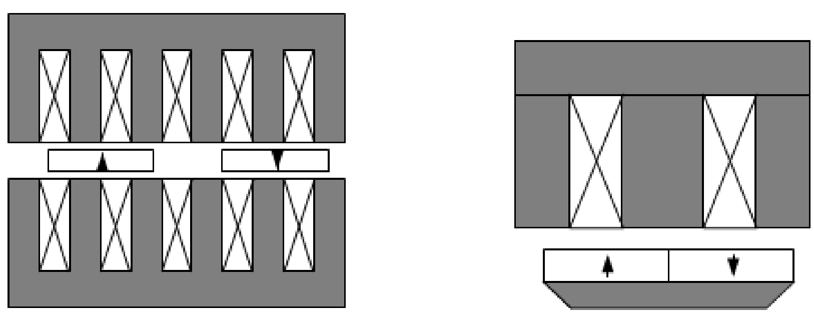


Figure 10: Planar configurations of slotted linear motor [9]

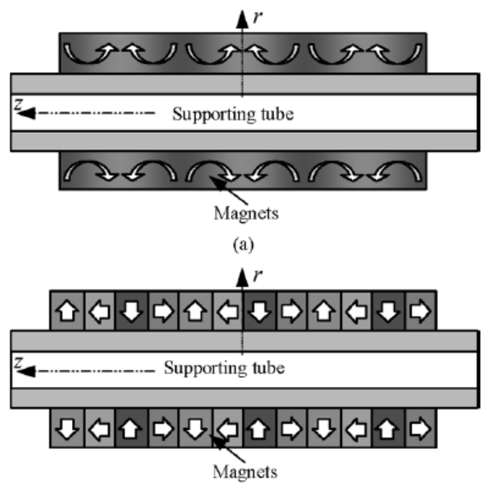


Figure 11: Tubular configurations of slotted linear motor [9]

Tubular permanent magnet machine offer a high efficiency, high power or force density, and excellent servo characteristic which make them particularly attractive [18]. Moreover, to reduce cogging force in the slotted linear permanent magnet motor, extra tool will be added to the stator design in order to reduce cogging n end effect force. Cogging force in slotted permanent magnet linear motor is caused by slotting and end effects.

Slotting effect is due to the interaction between permanent magnet and the armature slotted core with the wavelength of one slot pitch. While the end effect force arise from the interaction between permanent magnet and the finite length of armature core with the wavelength of one pole pitch. Therefore, several techniques had been proposed in order to reduce these forces such as proper pole and slot combination selection, magnet length adjustment, auxiliary pole (APs) utilizing and magnet or slot skewing. Figure 12 shows the APs is inserted in order to reduce the cogging force [19] [20].

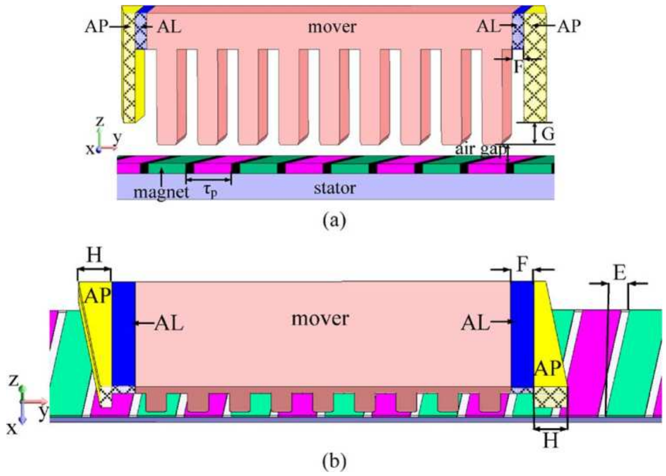


Figure 12: Two APs are fixed in both side of the mover [20]

2.3.4.2 Slotless permanent magnet linear motor

Moving magnet linear motor has been designed for widely varying applications, such as air compressor, artificial hearts, automotive systems, and robotics [1]. Various possible design variants for both planar and tubular linear motor have been compiled. The linear motor as shown in Figure 13 and Figure 14 encompassing slotless stator, permanent magnet and permanent magnet with ferromagnetic armature and variable constant air-gap design.

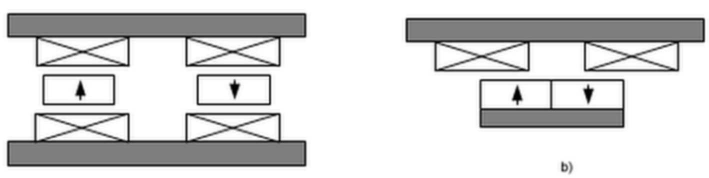


Figure 13: Planar configurations of slotless linear motor [9]

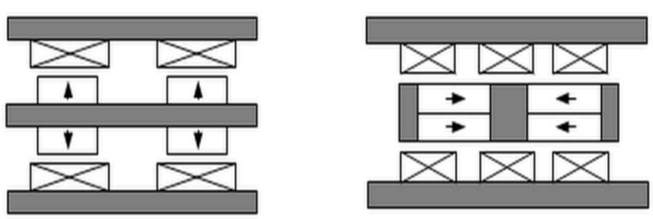


Figure 14: Tubular configurations of slotless linear motor [9]

However, there are few techniques to improve the force density in linear permanent magnet motor which is the selection of the shape of permanent magnet. It has been shown that in slotless tubular permanent magnet actuators using quasi-halbach magnetization patterns have a number of attractive characteristics, such as a sinusoidal back-emf force waveform, which result in very low electromagnetic force ripple and the possibility of being optimized to achieve almost zero cogging force [21]. Figure 15 shows the quasi-halbach magnetization pattern using rectangular square permanent magnet and trapezoidal shape permanent magnet.

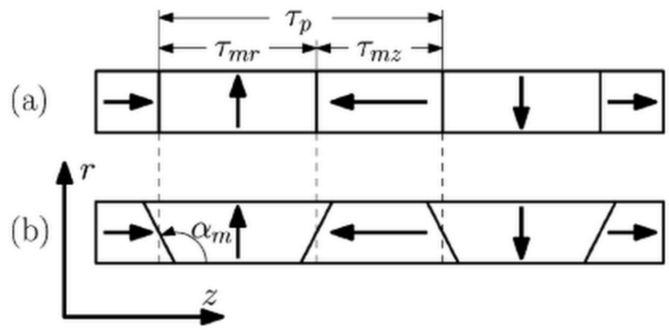


Figure 15: Quasi-Halbach magnetization pattern. (a) Rectangular square permanent magnet (b) Trapezoidal Shape permanent magnet [21]

2.4 Proposed Design

Literature review has been conduct in order to produce the most suitable design for linear compressor. The author has came out with the suitable design that full the requirements of the applications though, the most important criteria to produce linear motors for air-vapor compressor applications are based on their force capability, simplicity and cost-effectiveness. Therefore, the moving-magnet tubular slotless linear motor with mild steel stator manufactured has been choosing.

Three proposed design have been selected for further analyses which are tubular slotless linear motor using rectangular/trapezoidal PM with the magnet arrangement is separately with mild steel and also quasi-halbach slotless linear motor with rectangular PM. The magnet configuration for tubular slotless linear motor is radially magnetization. In all three designs, the quasi-halbach magnetized armature generates a magnetic field which links with the single-phase stator coil, and there is thrust force produce on order to make interaction between permanent magnet magnetic field and the stator current [9].

In terms of the stator configuration, there are additional of auxiliary pole (APs) in order to reduce the cogging and end effect force. Also, with having this APs the flux will linkage rather than leakage to the side. For a stronger air-gap field and force capability, ferromagnetic tube will be used as a supporter to the radially and quasi-halbach magnetized motor with trapezoidal and rectangular magnet proposed design. Figure 16 and Figure 17 show the tubular slotless linear motor using trapezoidal/rectangular PM while Figure 18 shows the quasi-halbach slotless linear motor.

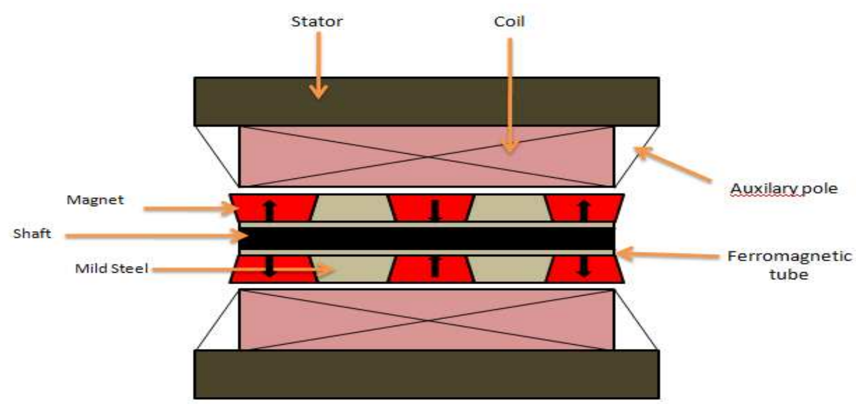


Figure 16: Tubular slotless linear motor with trapezoidal PM and the magnet arrangement separately with mild steel

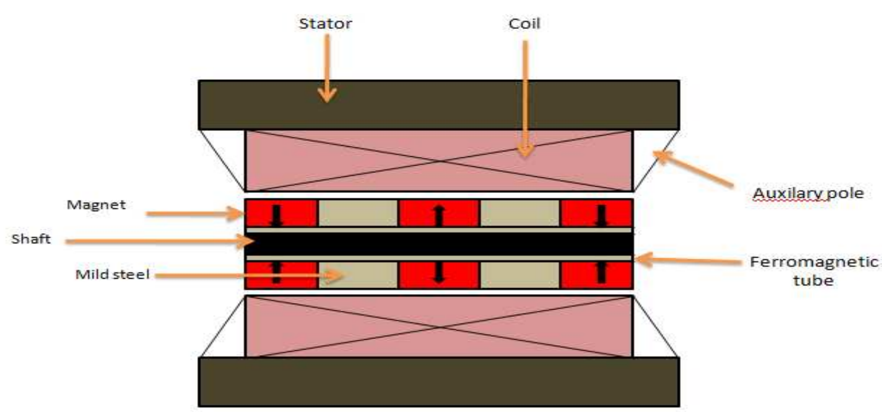


Figure 17: Tubular slotless linear motor with rectangular PM and the magnet arrangement separately with mild steel

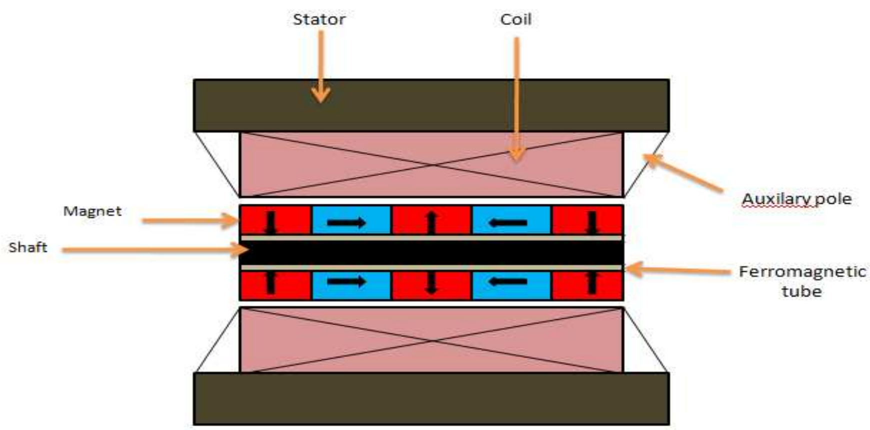


Figure 18: Quasi-halbach slotless linear motor

2.4 Conclusion

Various types of linear machine have been studied and discussed in this chapter such as linear synchronous machine, linear DC machine, linear induction machine and also linear permanent magnet machine. Linear permanent magnet machine (moving magnet) has been chosen to be applied into the design of linear motor for air vapor compressor due to its characteristic that have high performance at low speed, high force capability and also high efficiency. In the other hand, slotless linear permanent magnet motor has been chosen because it can produce high speed due to slotless design and also it can reduce cogging and end effect force. Three designs have been proposed which are tubular slotless linear motor using rectangular/trapezoidal permanent magnets with the magnet arrangement separately with mild steel and also tubular slotless linear motor with rectangular permanent magnet.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter involves the methodology and design specifications of all proposed designs. The shape of the permanent magnet is taken into consideration. All of the proposed design will be simulate using finite element analysis which used ANSYS software. Besides, the characteristics of different permanent magnet remanence will be discussed in this chapter and the decision of which types of permanent magnet to be applied to the motor will be determined. However, the graphic result by using flux lines distribution of which magnet is the best to choose will be shown in the next chapter.

3.2 Procedure Identification

The methodology starts with problem identification of the project. The main problem that has been determined is due to the refrigerator compressor. Conventional compressor produces high power consumption due to its crank-drive piston. After the problem has been determined, the author proceeds with the literature review. Several literature reviews has been conduct on four topologies of linear motor in order to choose the best topologies to be applied to the compressor. After done with literature review, the author has come out with three proposed design based on motor topologies that have been chosen. The proposed design is proposed based on type of permanent magnet, the stator design of the motor, and also the shape of permanent magnet that will be used. Then, design parameter and specification of all the proposed design has been done using finite element software which is ANSYS software. The parameter that been taken into consideration are flux line distribution, air-gap flux distribution plot and also moving force plot. The design parameter is simulated until the satisfy design is been determined. The last step is the result and discussion based on the simulation and also thesis writing. The flow chart of the methodology is illustrate in figure 19.

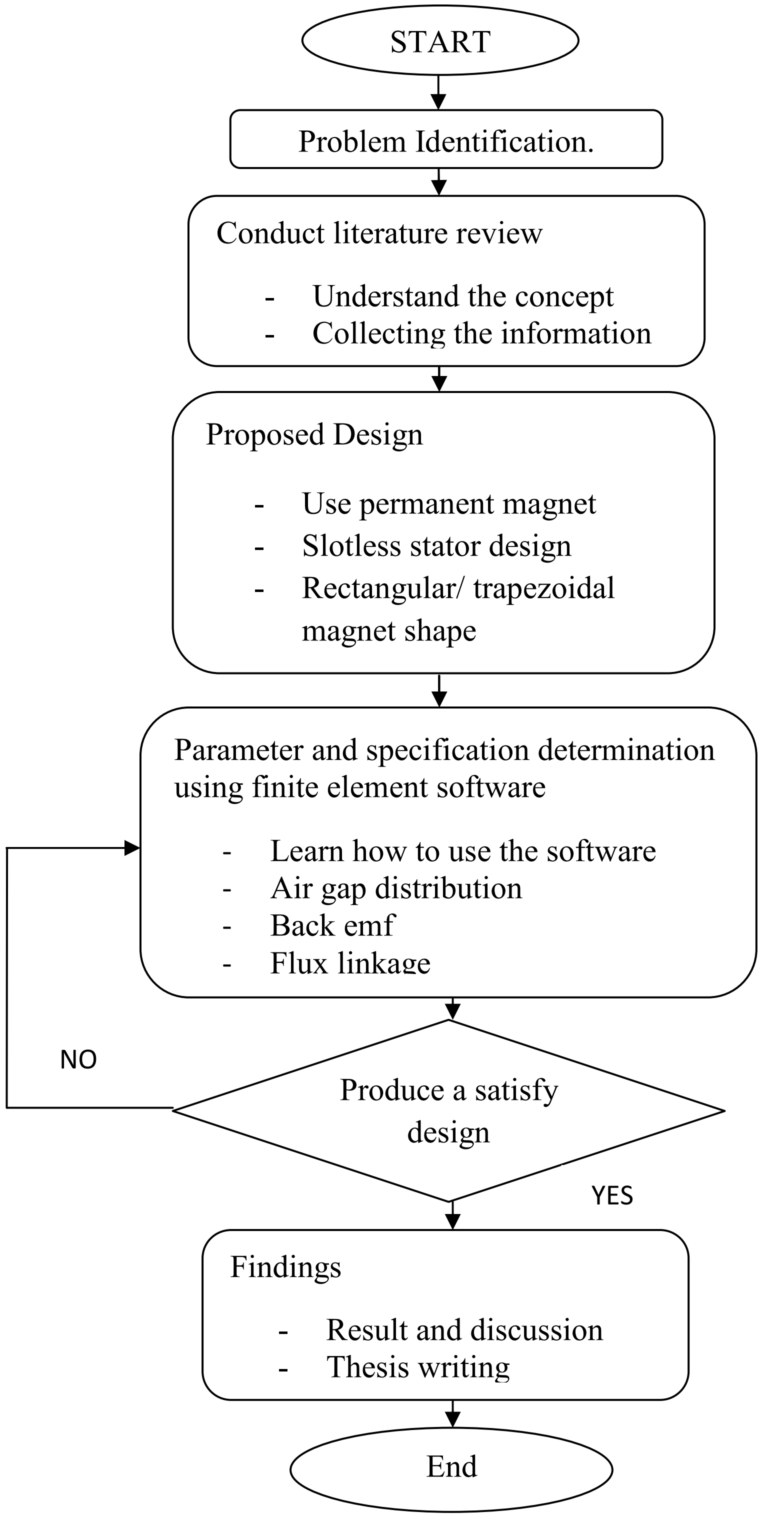


Figure 19: Project Flow

3.3 Elements Determinations

In this project, the author decided to use the concept of linear permanent magnet motor. The elements that constrain to produce the best design will be determined and a few studies about the key elements of the linear permanent magnet motor have been studied.

3.3.1 Type of Magnet

In this project, a few types of magnet have been tested to the linear motors which are Neodymium Iron Boron (NdFeB), Samarium Cobalt (SmCo) and Alnico (Al). The type of magnet is chosen based on the flux lines distribution result that gets from the simulation using ANSYS software.

Table 1: Comparison of Magnetic Performance of Three Type of Magnet [27]

Magnet	M_r (T)	H_{ci} (kA/M)	BH_{max} (kJ/m^3)	T_c (°C)
NdFeB	1.0-1.4	750-2000	200-440	310-400
SmCo	0.8-1.1	600-2000	120-200	720
Alnico	0.6-1.4	275	10-88	700-860

3.3.2 Arrangement of Permanent Magnet

On the other hand, the arrangement of the magnet is also taken into consideration because it can determine the performance of the linear motor as well. In this project, there are three types of magnet arrangement has been design which are radially magnetized using trapezoidal/rectangular shape of permanent magnet and Quasi-Halbach arrangement of magnet using rectangular shape of permanent magnet.

3.3.2.1 Trapezoidal Shape of Permanent Magnet

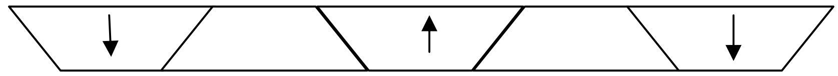


Figure 20: Trapezoidal Shape of Permanent Magnet with Radially Magnetized

3.3.2.2 Rectangular Shape of Permanent Magnet

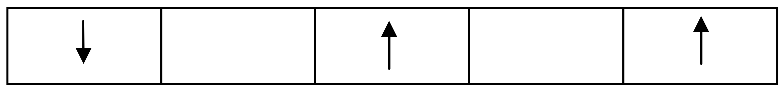


Figure 21: Rectangular Shape of Permanent Magnet with Radially Magnetized

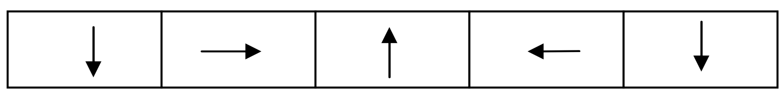


Figure 22: Rectangular Shape of Permanent Magnet with Quasi-Halbach Magnetized

Figure 20, 21 and 22 show the arrangement of permanent magnet using trapezoidal shape permanent magnet and rectangular shape permanent magnet. The arrangement of the permanent magnet that has been taken into consideration is radially magnetization pattern and quasi-halbach magnetization pattern. Both radially and quasi-halbach magnetization pattern can gives good performance to the linear motor. However, to prove which magnetization pattern is the better, the design will be simulated using ANSYS software.

3.4 Application Tool

The application tool that been using throughout the project is ANSYS software. The method use is finite element method (FEM) or practically known as finite element analysis (FEA) is a numerical technique for finding approximate solutions of partial different equation (PDE) as well as of integral equations. Finite element analysis will be use to analyze the magnetic characteristic, magnetic flux density, and also moving force that shown in ANSYS. ANSYS is software that widely use in the computer-aided engineering (CAE) field. ANSYS software allows engineer to construct models of structure and machine component or system. This software has a variety of design analysis applications, ranging from such everyday items such as dishwashers, automobile, and refrigerator to highly complicated systems such as bridges, X-Ray equipment, and orbiting satellites. In this project, a 2-Dimensional shape of linear permanent magnet motor will be drawn using this ANSYS software. The analysis and comparison on air-gap flux density and moving force of the three designs will be conducted.

3.5 Methodology of Using the ANSYS Software

In the ANSYS software, for the linear motor drawing, it has two modes which Maxwell 2D-Design Project and Maxwell 3D-Design project. For the purpose of this project, the Maxwell 2D-Design project will be use. Below shows the step on how the project will begin:

1) Insert Maxwell 2D-Design project
2) Set the solution type to transient mode
3) Select the tool to start draw the design.
4) Assign boundaries of the object
5) Assign material of the object
6) Assign mesh operation of the object
7) Assign the excitation of the coil
8) Assign the parameter needed
9) Set the solution setup
10) Validate the project
11) Analyze the project

After the project has been analyze, then the result can be viewed in term of graph plot. For this project, the air gap flux density and moving force graph is needed. On the other hand, flux line distribution, magnetic flux density and mesh plot can also be viewed.

3.5 Conclusion

A few specifications of the three proposed design have been discussed. The characteristic of the three types of permanent magnet have been determined which NdFeB type of permanent magnet is selected. The different shapes of permanent magnet such as trapezoidal and rectangular are also been determined. The advantages and disadvantages of the two shape of permanent magnet have also been stated. The ANSYS software has been used to simulate the proposed design in order to determine the air-gap flux density and also moving force of the design.

CHAPTER 4

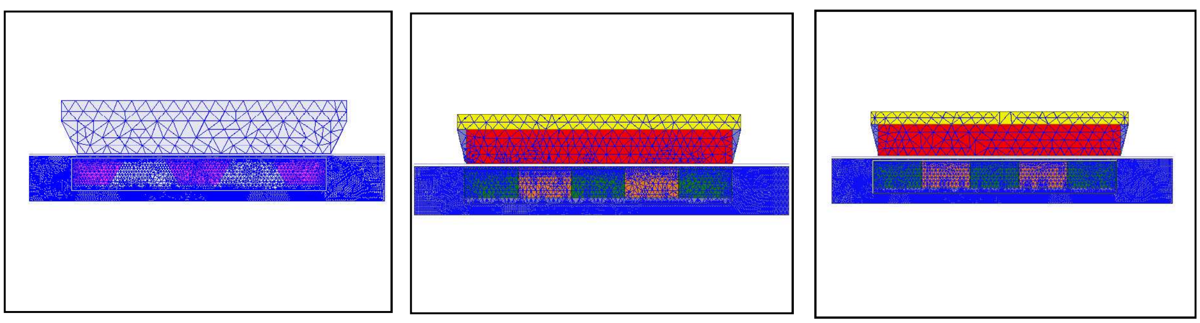
RESULT & DISCUSSION

4.1 Introduction

This chapter illustrates the results and discussion on linear permanent magnet motor which have been proposed in chapter 3 whereby the results are concentrated in air gap flux density and moving force. Also, the three designs are compared based on type of magnet use. In this project, there are three types of magnet that taken into consideration which are Alnico, Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB).

4.2 Mesh Plot for All Three Proposed Design Using SmCo Type of Magnet

As will be observed, Figure 23 (a), (b) and (c) shows the mesh plot for the three proposed design.



(a) **(b)** **(c)**

Figure 23 (a)Trapezoidal Magnet (b)Rectangular Magnet (Radially Magnetized) (c)Rectangular Magnet (Quasi-Halbach Magnetized)

The mesh operation is needed as first step to see whether the design is acceptable or not. All of these design used the same mesh setting. However, the mesh setting is differing for magnet, band area and also inner region. For magnet and band area, the number of element used is 1000 while for the inner region, the number of element used is 5000. The more number of elements, the smallest mesh plot drawn. The small the mesh, the calculation is more accurate. Therefore, for all the designs, the mesh plot is already acceptable to move to another step which to select the best design based on air-gap flux density and moving force.

4.3 Comparison of Open Flux Distribution for Three Proposed Designs with Three Different

Types of Magnet

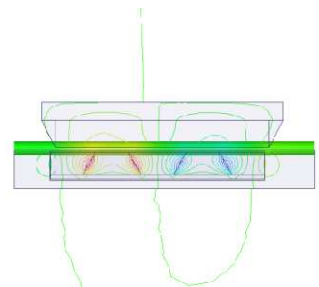
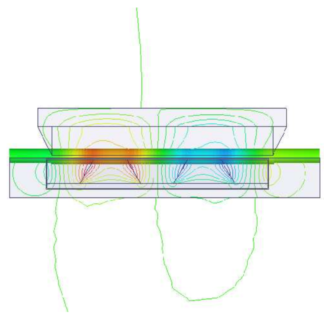
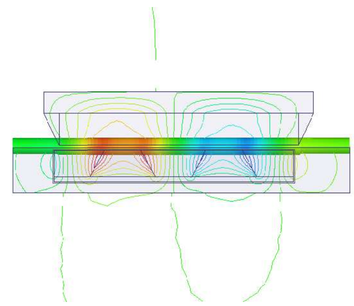
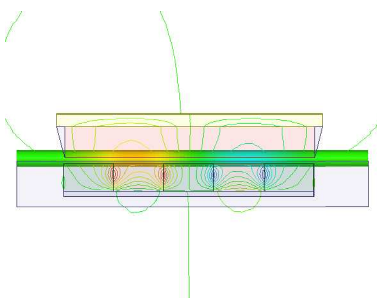
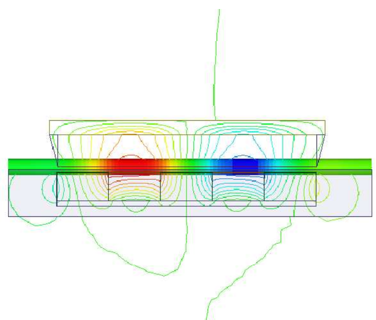
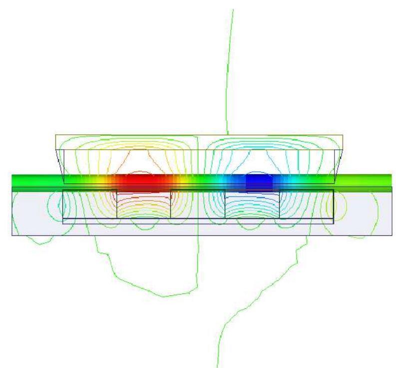
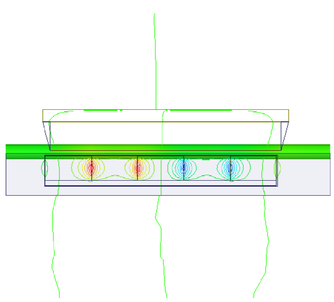
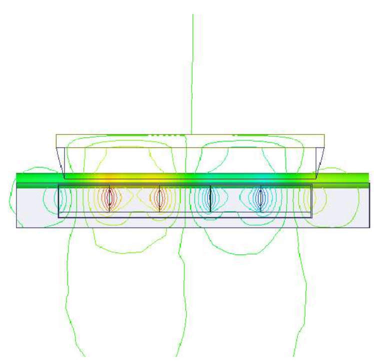
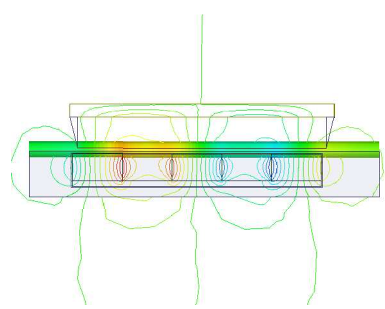
Design / Alnico	SmCo	NdFeB
1) **Design A** 		
2) **Design B** 		
3) **Design C** 		

Figure 24: Magnet Type Comparison

Figure 24 shows the comparison of flux line distribution for three types of proposed design using three different types of magnet. For SmCo permanent magnet, the remanence of the magnet use is 1.01Tesla while for NdFeB, the remanence of the magnet is 1.05Tesla and remanence of the Alnico is 1.27Tesla. Although the Tesla of the alnico permanent magnet is high, it is not shows that it has high flux density. This is because; Alnico is non-linear permanent magnet which has low magnetic field.

As will been seen, the SmCo and NdFeB type of magnet shows slightly similar flux distribution plot while Alnico have slightly different from the other two types of magnet. This shows that alnico do not strong enough to have a contact with the stator. This result is agreed for all proposed design. This will result lack of magnetic field produce thus lower the performance of the motor. On the other hand, SmCo and NdFeB is rare earth magnet so that it is a strong magnet. It can produce high magnetic field thus increase the performance of the motor. However, the SmCo type of magnet will be chosen because it has lower price than NdFeB.

4.4 Air-Gap Flux Density for Three Proposed Design

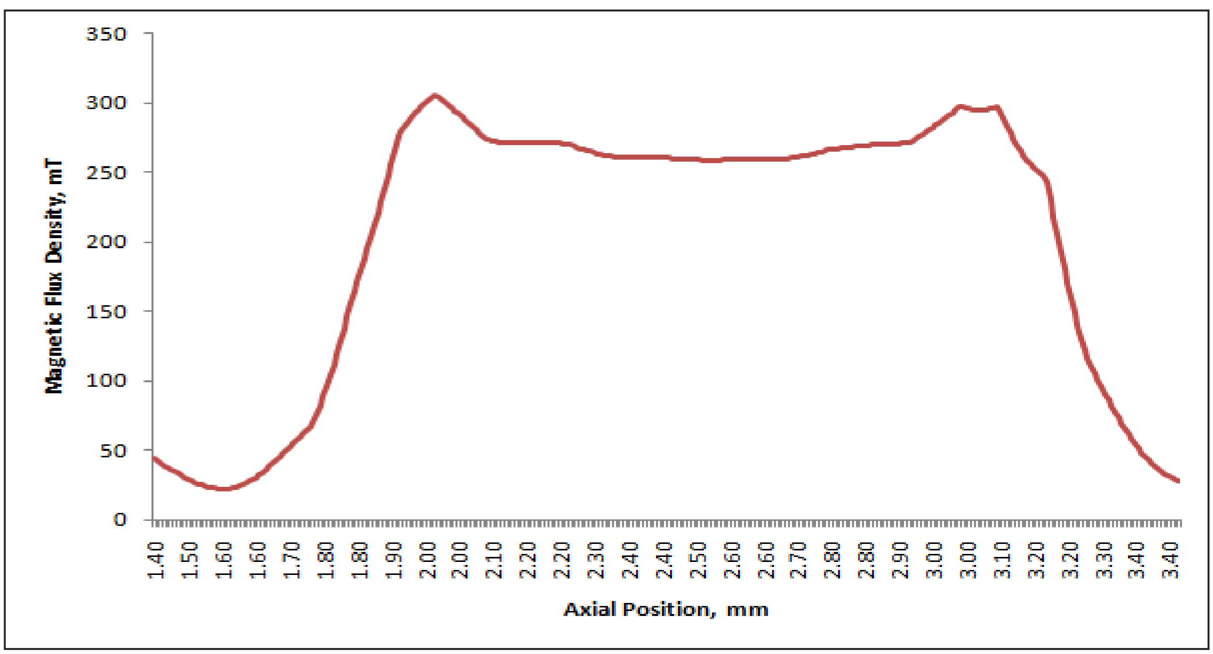


Figure 25 : Air-Gap Flux Density for Design A

Figure 25 shows the air gap flux density of trapezoidal shape of permanent magnet. The maximum flux density can reach is 0.32 Tesla. However, the average value of the flux density is 0.19 Tesla.

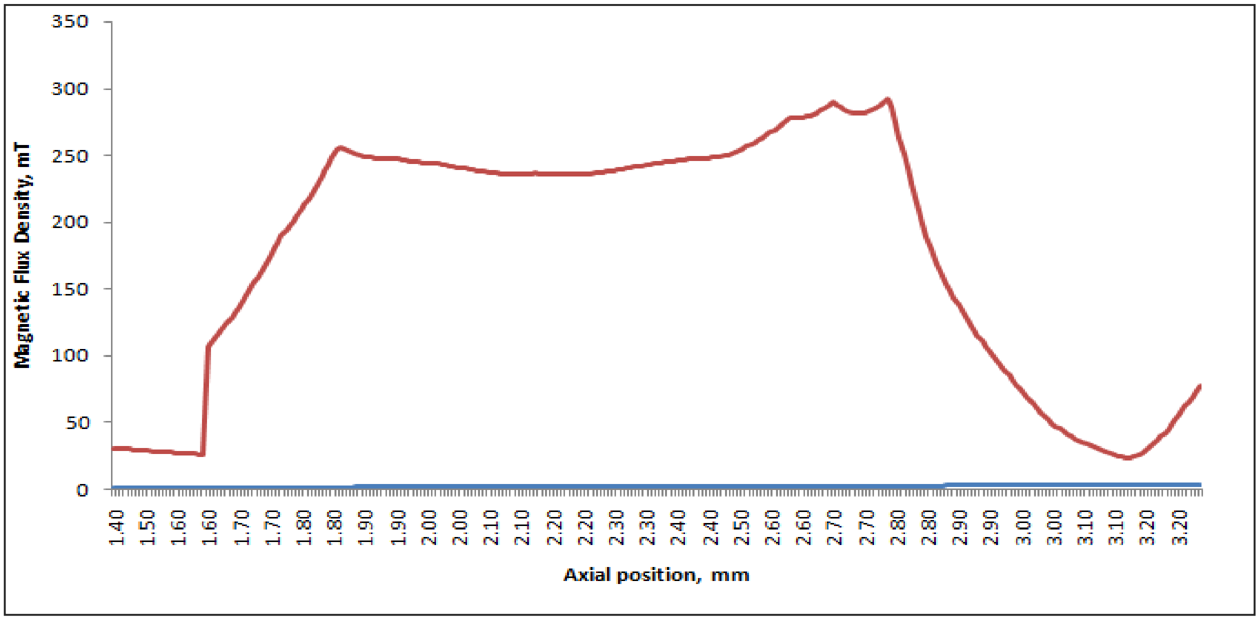


Figure 26: Air-Gap Flux Density for Design B

Figure 26 shows the air gap flux density plot for rectangular shape of permanent magnet with radially magnetization pattern. The maximum height that the flux can reach is 0.36 Tesla. The average value is 0.2 Tesla.

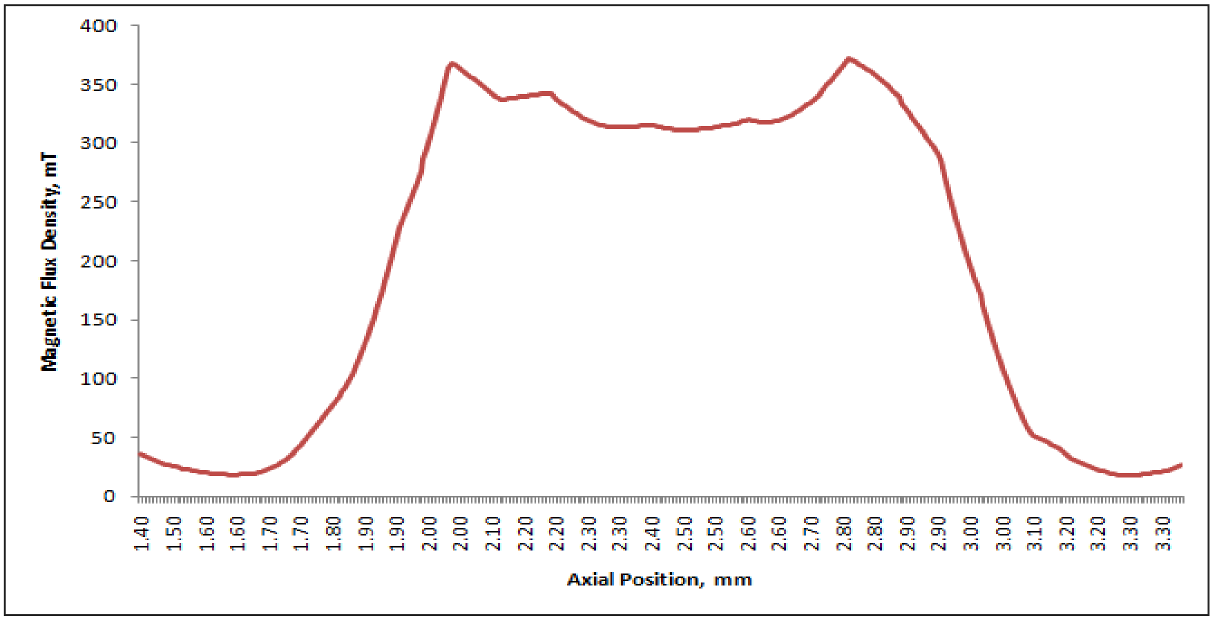


Figure 27: Air-Gap Flux Density for Design C

Figure 27 shows the air gap flux density for rectangular shape of permanent magnet with quasi-halbach magnetization pattern at zero displacement. The maximum height the flux can reach is 0.37 Tesla. The average value of the flux density is 0.22 Tesla

4.5 Comparison of Air-Gap Flux Density for the Three Proposed Design

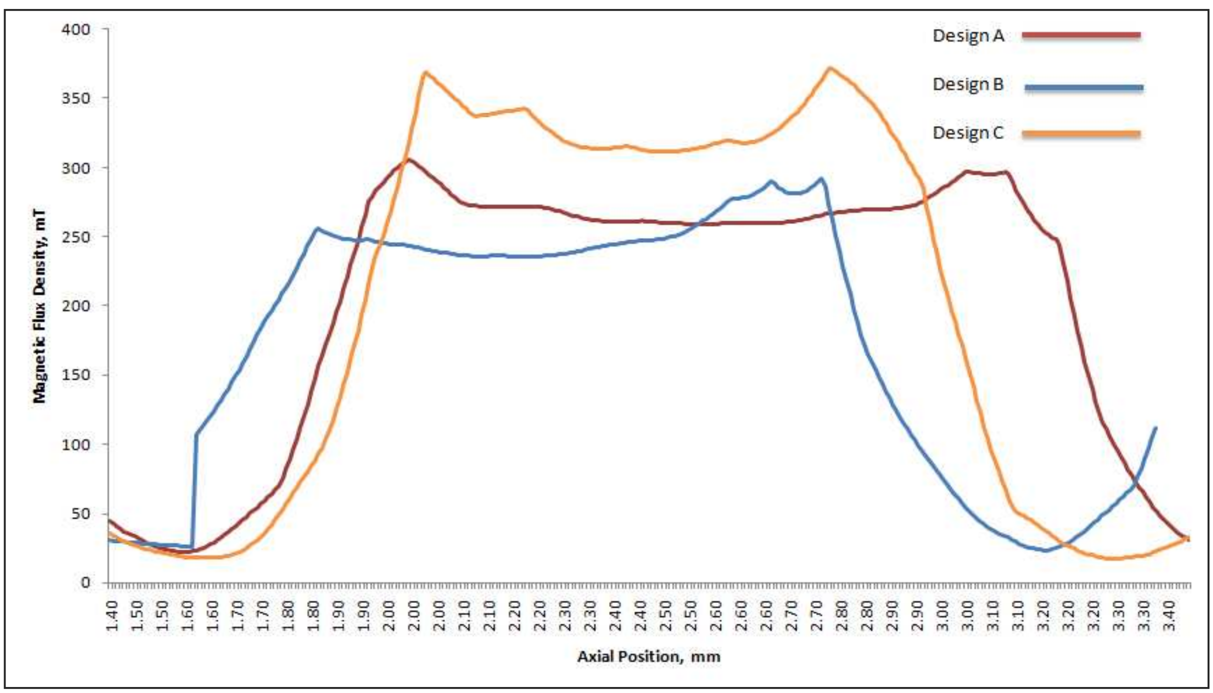


Figure 28: Comparison of Air-Gap Flux Density between Three Proposed Designs

Figure 28 shows the comparison between the three proposed designs. Design A and design B have about similar air-gap density for the half of the axial position but different towards the end. Design C tend to have higher flux density and have different plot than design A and B. all of this designs used same type of magnet which is NdFeB and the remanence of the magnet is 1.1T. The air-gap of all the designs is 1mm. Based on the plot; design C has higher average value of flux density. The shape of the plot is slightly similar to the previous design. Therefore, as for air-gap flux density comparison, it shows that, design C is better than the other two designs. In the next stage, comparison between the moving forces of all the design will be determined. The comparison just showed the moving force of all the design. After that, back EMF will be calculated as final stage before the best design can be chosen.

4.5 Comparison of Moving Force for the Three Proposed Design

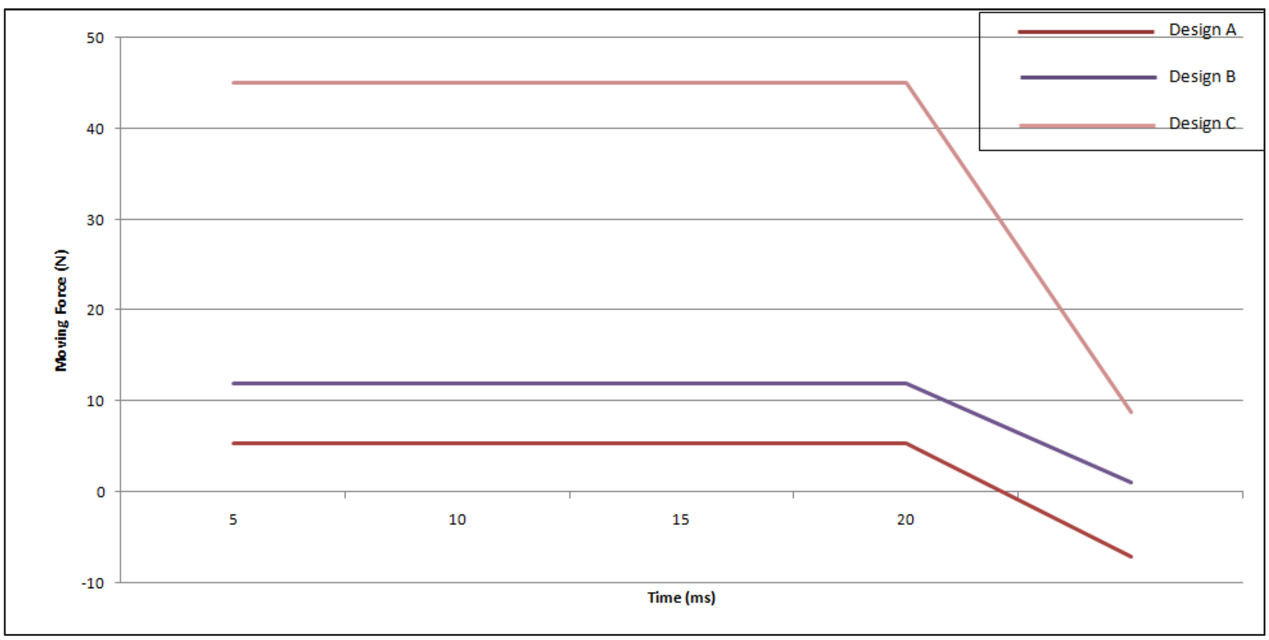


Figure 29: Comparison of Moving Force for Three Proposed Design

Based on the Figure 29, the moving force for all design has met the requirement. For the first design, the force is synchronous at first 4 seconds and then drop drastically at the 5th second. This shown that the moving part of the linear motor is stop at 5 second.

On the other hand, the force for design B n C is slightly same. The different is at the drop time. For design B, the force is synchronous from the beginning until at 18th second, then slightly increase at 19th second and then drop rapidly. As for design C, its force is synchronous at the beginning until 5th second, and then its increase slightly until the 7th second and slowly decrease until the last second.

The result for all the three proposed design is determined using the same solution setup in the ANSYS software. The different result might be because of the shape of the permanent magnet and also the arrangement of the permanent magnet itself. However, the result still met the requirement. Therefore, the last stage before the best design can be chosen is based on the back EMF result.

4.6 Discussion

The proposed design of linear motor for air vapor compressor should have a result where it can reach a good performance when it is applied to the refrigerator. In the other hand, it also is being able to increase the efficiency of the compressor itself. However, there are pros and cons of each proposed design, but a balance point of the design should be made. The best design that will be selected should meet the requirement as state in the very first of this project and also the manufacturing cost should be taken into consideration. Therefore, the comparison of each proposed design is carries out.

4.6.1 Back EMF Calculation for All Designs

Back EMF is computed when the linear motor is moving. For this project, the motor is moving at a speed of 1 m/s and 0.5A current. The result has been captured using the ANSYS software.

The back EMF is calculated based on the equation given;

E $= k_w f B A N$

k_w = 4.44

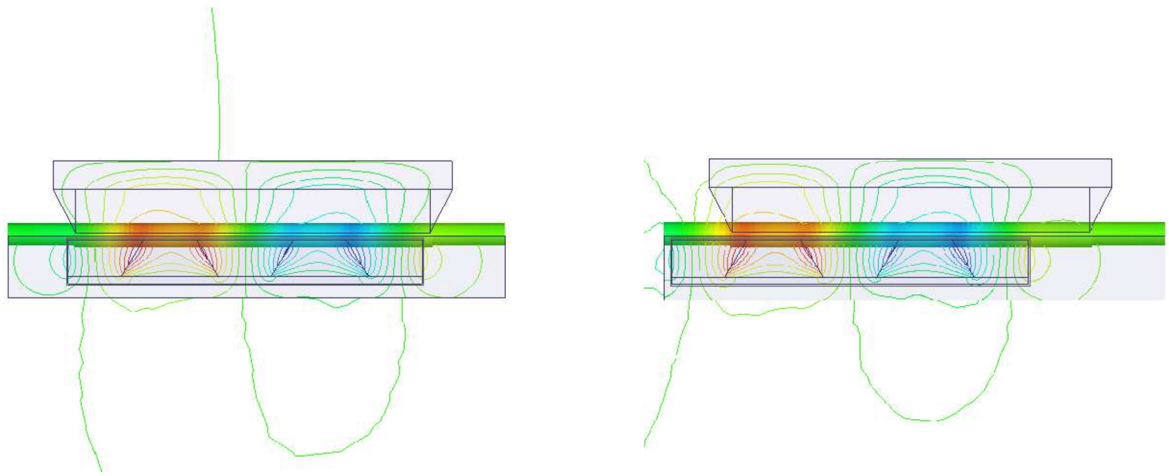
f = 50Hz

B = flux density generated

A = area of the magnet

N = number of turns of coi

For Design A;



(a) **(b)**

Figure 30 (a) x = 0.0mm (b) x = 10mm

Figure 30 shows the motion of the design A from zero position to 10mm position. The back EMF calculation for this design is shown below;

N = 650 turns

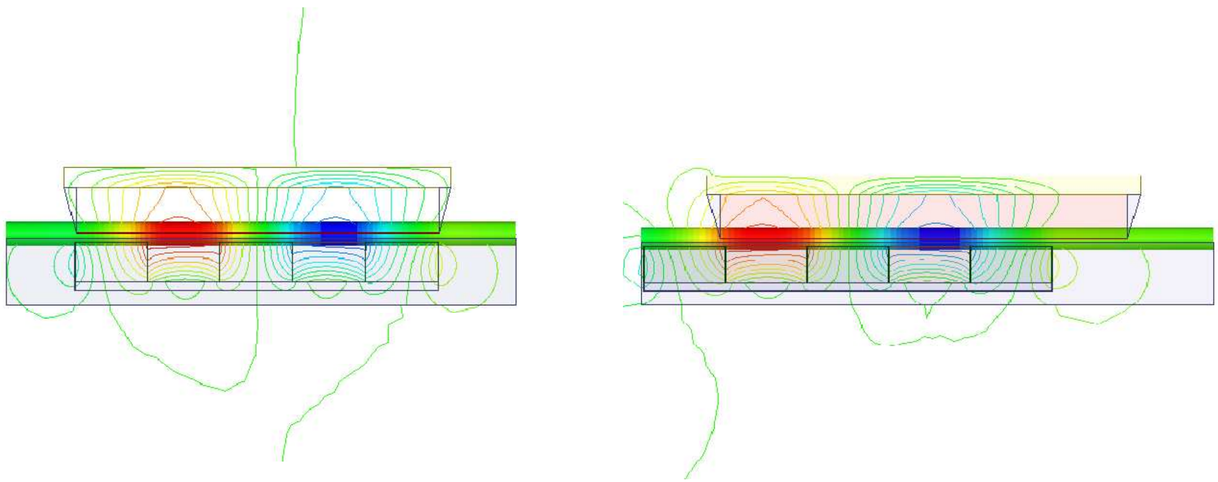
A = ((1/2 x 0.05 x 0.02) + (0.07 x 0.05))

= 4.0e-3 cm^2

E = 4.44 x 50 x 0.32 x 4.0e-3 x 150

= 184.7 V

For Design B;



(a) (b)

Figure 31 (a) x=0.0mm (b) x = 10mm

Figure 31 shows the motion of the design A from zero position to 10mm position. The back EMF calculation for this design is shown below;

N = 650 turns

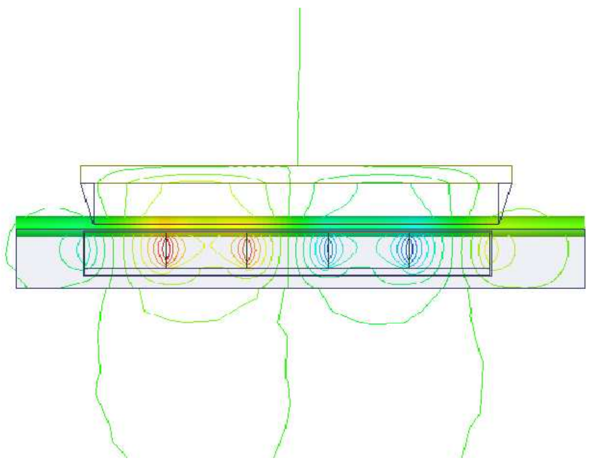
A = 0.054 x 0.094

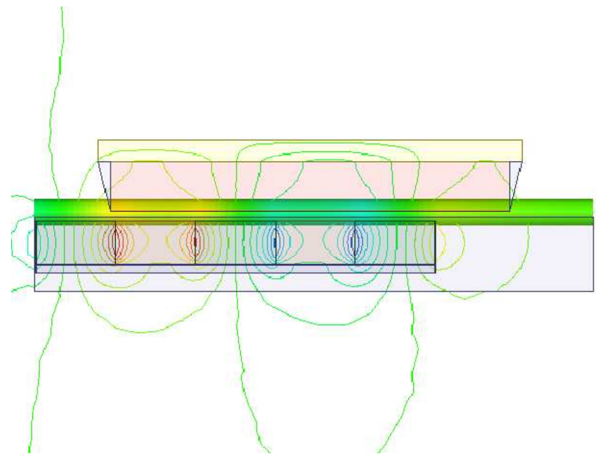
= 4.89e-3 cm^2

E = 4.44 x 50 x 0.365 x 4.89e-3 x 650

= 225.8 V

For Design C;





(a) **(b)**

Figure 32 (a) x=0.0mm (b) x = 10mm

Figure 32 shows the motion of the design A from zero position to 10mm position. The back EMF calculation for this design is shown below;

N = 650 turns

A = 0.054 x 0.094

= 4.89e-3 cm^2

E = 4.44 x 50 x 0.37 x 4.89e-3 x 650

= 261.08 V

Table 2: Magnetic Flux Density and Back EMF Comparison

Comparison / Design	Average Magnetic Flux Density (T)	Back EMF (V)	Average Moving Force (N)
Design A	0.320	184.7	2.87
Design B	0.365	225.8	7.80
Design C	0.370	261.08	26.24

Based on the back EMF result that have been determined, design C tend to be the best design because the it has higher back EMF rather than the other two design. The results are based on the motions that have been conduct in the ANSYS software. All of the design has been setup with same motion setup which the stop time is 0.01sec and the time step is 0.0005sec. It takes about 20 steps to finish the motion. The result also have been taken in the forth step and above. This is because, the first three step tend to be not accurate due to wrong calculation. So, all the result has been taken at fifth step which at 0.0025sec. The flux distribution of the motion of the three proposed design are shown in the figure 32, 33 and 34.

4.7 Conclusion

As conclusion, design C which the rectangular permanent magnet with radially magnetized is chosen as the best design among the three proposed design. The selection of the best design is based on the air-gap flux distribution and also the back EMF of the design. Design C has higher air-gap flux density from the other two design which it can reach about 0.37 T while the other two design just reach below 0.36 T. On the other hand, the back EMF for design C also had higher value than the other two designs which is 60.24V. Therefore, it has been prove that design C is the best design and will be selected as new design of linear motor for air vapor compressor.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Based on the literature review that have been conduct throughout the Final Year Project 1, the permanent magnet machine has been chosen to be use in the project because of its good performance at low speed, high efficiency and high reliability. Several topologies of various types of linear machine have been review such as Linear Synchronous Machine, Linear DC Machine and also Linear Induction Machine before the best topologies has been chosen. Besides, moving magnet of linear permanent magnet motor has been used since it is able to have high force capability and reliable to be used for heavy duty operation.

The three proposed designs has some different in their shape of permanent magnet and also the arrangement of the permanent magnet. The design A differ from design B and C from the shape of the permanent magnet. Design A has trapezoidal shape of permanent magnet while design B n C has rectangular shape of permanent magnet. Rectangular shape permanent magnet is easy to manufacture and thus lowering the manufacturing cost. On the other hand, trapezoidal shape of permanent magnet is difficult to manufacture, thus increase the manufacturing cost. However trapezoidal shape permanent magnet has higher flux density and induced EMF. The shape of permanent magnet for design B n C is equal, what make them different is the arrangement of the magnet. Design B has radially magnetized while design C has Quasi-Halbach magnetized.

As conclusion, slotless linear permanent magnet machine has been chosen to be applied into the refrigerator compressor due to its characteristic that has great performance at low speed, high force capability and also high efficiency. Three proposed design has been proposed and undergone a comparison phase in order to choose the best design. The result has been choose based on a few criteria as stated earlier which are force capability, simplicity and cost-effectiveness.

All of the three proposed design has been simulate using finite element method which use ANSYS software. The performance of the design is determined by the air-gap flux density and the back EMF. The higher the air-gap flux density, the design tends to be higher performance.

Design C has higher air-gap flux density from the other two designs. On the other hand, the back EMF for design C also had higher value than the other two designs which is 261.08 V. Therefore, it has been prove that design C is the best design and will be selected as new design of linear motor for air vapor compressor.

5.2 Future Work

Instead of doing comparison of the three proposed design by using air-gap flux density and moving force, an optimization also can be done so that the three proposed design will be more accurate in terms of the thick of the magnet or even the stator design.

Besides, a prototype can be produced in order to test and make sure the design meets with the simulation results. Validation of the prototype can be carried out. It can be tested using the real refrigerator compressor so that it can test the efficiency of the refrigerator itself.

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APPENDICES

No	Detail/Week	1	2	3	4	5	6	Mid Semester Break (7/02-11/02/2012)	7	8	9	10	11	12	13	14
1	Selection of Project Topic: A novel design of ceiling fan system.															
2	Preliminary Research Work: Research on literatures related to the topic															
3	Submission of Extended Proposal															
5	Proposal Defend															
6	**Project work :** • Familiarization using finite element software															
7	Submission of draft for interim report															
8	Submission of Interim Report Final Draft															

FINAL YEAR PROJECT 2

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Project work continue from FYP I**														
2	Submission of progress report.														
3	Submission of draft report.														
5	Submission of final report. Submission of technical report.														