MODELLING OF LINEAR PERMANENT MAGNET MOTOR FOR AIR-VAPOR COMPRESSOR

By

AZRINA BINTI HISHAMUDDIN

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial fulfilment of the requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK
June or December 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 sources or persons.

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AZRINA BINTI HISHAMUDDIN

ABSTRACT

Power consumption of refrigerator is the top three among the various household appliances. This is because of the lack performance and efficiency of the conventional refrigerator compressor system.

This paper describes about the design of linear permanent magnet motor for reciprocating air-vapor compressor application. There are various types of linear motor technologies and topologies for air-vapor compressor that have been discussed, such as, linear induction machine, linear synchronous machine, linear DC machine, and linear permanent magnet machine. The significant designs criteria considered are based on their force capability, higher efficiency, simplicity and cost-effectiveness. Among the linear motor technologies reviewed, a linear permanent magnet machine is the most preferable technologies for the reciprocating air-vapor compressor application due to the high thrust capability and efficiency. There are three categories of the linear permanent magnet, which are, moving-coil, moving-iron, and moving-magnet.

This paper is mainly focused on the moving-magnet topologies which considered a tubular permanent magnet, a slotted and a slotless stator, and also a different type of magnet configuration for the reciprocating air-vapor compressor application. The linear permanent magnet topologies have been studied and analyzed in order to obtain the best three designs for the reciprocating air-vapor compressor application.

ANSYS software, ANSOFT Maxwell, is used to draw and analyze the proposed designs to get the results of air-gap flux distribution, air-gap flux density and the respective graph. The result for the three designs will be compared discussed in order to choose one best design for air-vapor compressor application. In conclusion, the best design obtained can be apply for air-vapor compressor to increase efficiency, performance and reduce the energy consumption as well.

ACKNOWLEDGEMENT

First of all I would like to be thankful to God Almighty, because of Him I finally completed my Final Year Project. He gave me bless, strength and ideas in order for me to complete my project successfully

I would also like to thank to my Final Year Project supervisor, Dr.Taib bin Ibrahim who has guided me throughout the project. He gave me suggestion, opinion and information needed to complete the project. His professionalism and expertise has been helping me to do well in this project.

Furthermore, I would like to thanks to Universiti Teknologi PETRONAS (UTP) for the study's opportunity and the valuable knowledge that I experienced. I would also like to thank to my sponsor, Jabatan Perkhidmatan Awam (JPA) for their support during my study in UTP.

Besides, I would like to thank to my family for their full support during I am struggling to complete the project. Their endless support gives me strength and courage to go through every challenge that I have to face during Final Year Project.

Last but not least, my great appreciation also dedicated to all friends who help and support me directly or indirectly.

I hope that everything that I learnt during the Final Year Project will be benefit for me in the future. Thank you for all their help, support and consideration.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter involves the background of study and problem statement about designing a linear motor for air-vapor compressor to improve its efficiency and reduce energy consumption as well. This is due to the lack performance of the conventional refrigerator that using an induction motor to drive the reciprocating pump through a crank. This chapter also includes the objectives and scope of studies of the project.

1.2 BACKGROUND OF STUDY

Worldwide energy consumption has risen up every year and the demand of the energy is expected to increase significantly [1]. For example, in Asia, electricity consumption growth exceeded 10% (Rumsey 1995) by the early 1990s, due to urbanization, the rise of industrial sector, and the emergence of a new middle class [2]. Nowadays, the manufacturing sector, together with the country that involve in economic growth, consumes as much energy as developing country. The continuously increase of energy consumption demand will give effect on energy supplies in the future.

Among the various household appliances, refrigerator is the top three of the major energy consuming, which is about 597 kWh of the energy consumption at home [3]. This is shown in the Fig. 1.1, which means that, refrigerator is one of the, major energy consuming at home. The use of higher efficiency compressor can considerably reduce the consumption of energy for refrigerator. Since the refrigerator compressor is driven at a low speed, thus, the energy can be saved by improving the motor driving efficiency in low speed drive.

Therefore, as mention by Taib, cost-effective measures to improve the motor driving efficiency are highly recommended to save the world energy consumption [4].

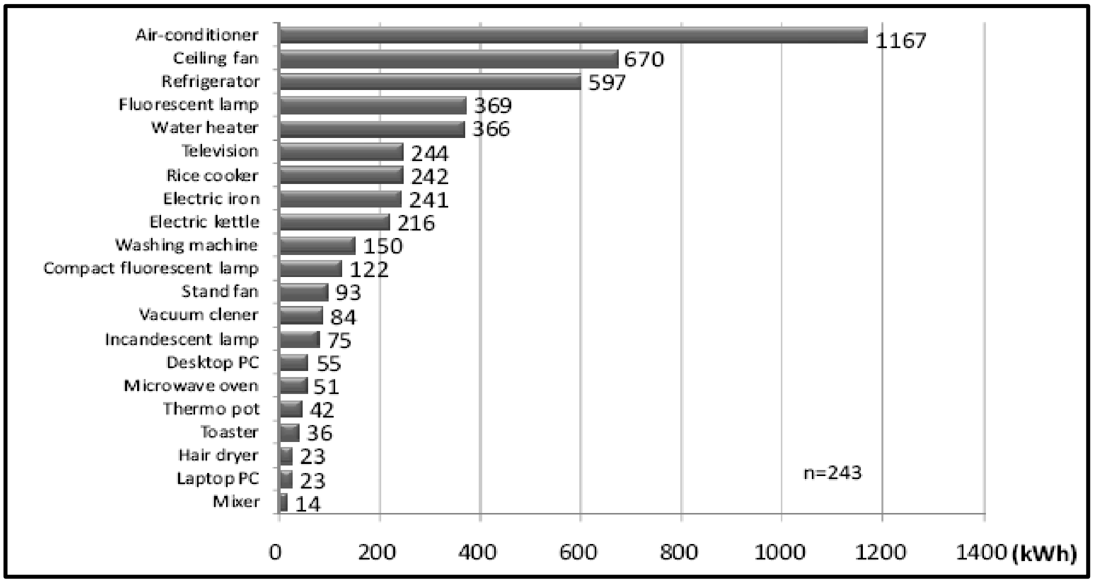


Fig. 1.1 Yearly Energy Consumption [3]

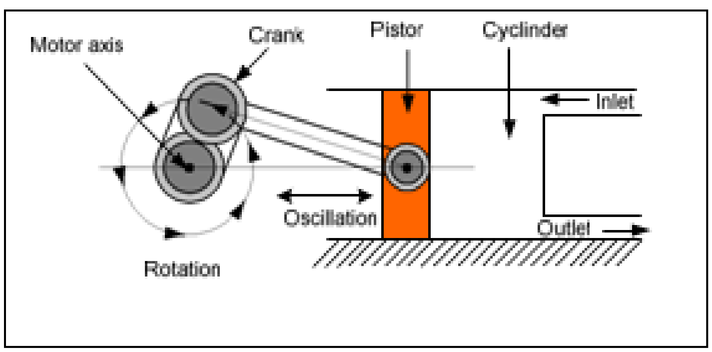


Fig. 1.2 Schematic of conventional refrigerator compressor [4]

In a conventional refrigerator compressor, a rotary electrical motor, usually an induction motor drives a reciprocating pump through a crank [5]. The low efficiency of the induction motor, as well as the mechanical friction associated with the crank-driven piston has affected the overall efficiency of the refrigerator compressor system. Fig. 1.2 shows the schematic of conventional refrigerator compressor that uses a low efficiency of induction motor.

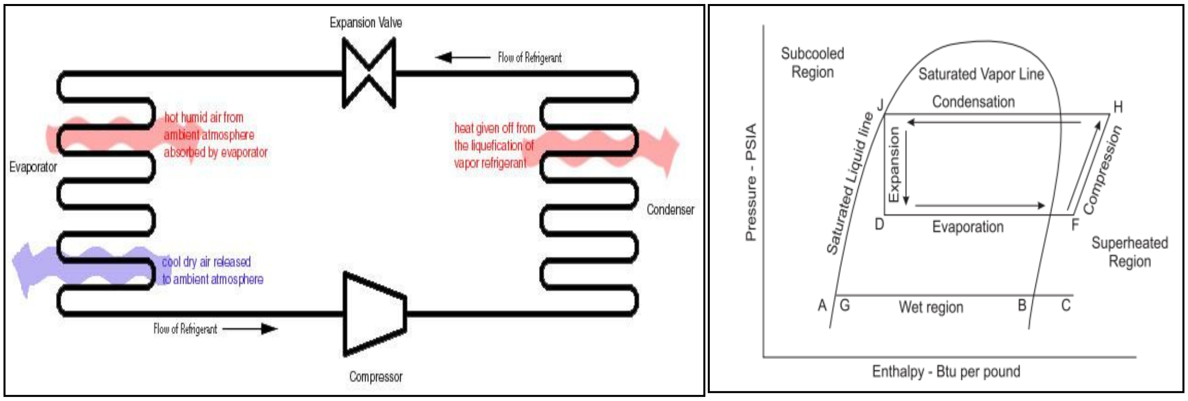


Fig. 1.3 Refrigeration Cycle [6]

Fig. 1.3 shows the basic cycle of the compressor in the refrigeration system [6]. As the refrigerant gas flows through the compressor, the compressor will raises its temperature. Next, the compressed refrigerant gas flows through the condenser, where it condenses from vapor form to liquid form. Then, the condensed refrigerant gas goes through an expansion valve. This reduces the pressure and the refrigerant expands and evaporates. Finally, the refrigerant gas draws heat from the evaporator, which causes it to vaporize.

Due to the weakness of the induction motor to drive the reciprocating air-vapor compressor, a direct-drive linear motor has been introduced to replace the induction motor for the compressor system [5]. The direct-linear motor is chosen because it eliminates the side force on the cylinder wall caused by the crank shaft. It is not only significantly reduces the frictional loss but also gives addition energy saving.

Fig. 1.4 illustrated the schematic of direct-drive linear compressor which employ a low-cost, single-phase linear permanent magnet (PM) motor [7]. The system is eliminates crank shaft in order to reduce friction loss.

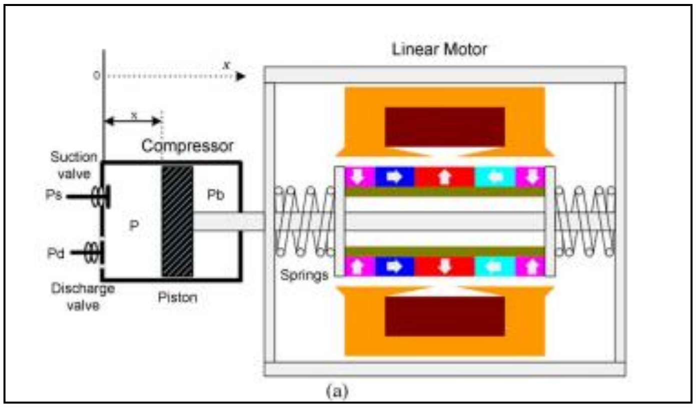


Fig. 1.4 Schematic of direct-drive linear compressor [7]

Obviously, the design of the linear motor will determine the performance of the direct-drive linear reciprocating air-vapor compressor operation, as well as reduce the energy consumption. The research from this paper will be analyzed about the various types of linear motor topologies to predict the best performance and efficiency of the reciprocating air-vapor compressor application.

1.2 PROBLEM STATEMENT

As mentioned earlier, energy consuming in the world is quite higher from time to time. This phenomenon is highly concern because the energy supplies are decreasing especially for non-renewable energy.

In Malaysia, among the various type of household appliances, refrigerator is experiencing a dramatic growth in energy consumption at home. The energy consumption of refrigerator has significantly caused by the efficiency of the compressor system [3]. Therefore, the higher efficiency of air-vapor compressor is able to decrease the use of energy consumption of refrigerator.

However, for the conventional refrigerator, an induction motor is used to drive a reciprocating pump through a crank [5]. This will result in a lower efficiency operation of compressor due to the low efficiency of the induction motor itself. Fortunately, a direct-drive linear motor has been introduced to replace the induction motor for the air-vapor compressor. This is because, the direct-drive linear motor eliminates the weakness of an induction motor. Therefore, the best optimized design of the linear motor for air-vapor compressor is able to increase the performance and efficiency of the reciprocating air-vapor compressor, as well as reduce the energy consumption.

1.3 OBJECTIVES AND SCOPE OF STUDIES

The aim of the research was to design and model a reciprocating linear motor for use in domestic refrigeration compressor systems. The specific objectives were:'

FYP 1

- To carry out literature review on linear motor topologies.
- To identify the most promising candidate topologies of linear reciprocating motor.
- To propose new design of permanent magnet linear motor for air-vapor compressor.

FYP 2

- To analyze the proposed designs by using ANSOFT Maxwell software, ANSYS.
- To choose a best design for the reciprocating air-vapor compressor.

SCOPE OF STUDIES:

1. Conduct literature review

First of all, the author conducts a literature review about the various types of linear motor topologies and technologies. The author searched and found the journals from the IEEE's website in order to get the sources. The author also gathered information from the internet and related magazines. The author studied and analyzed the technologies of linear motor especially for the reciprocating air-vapor compressor application in order to fully understand the concept and design.

2. Selection of proposed design

From the previous established designs, the author proposed three best designs for the reciprocating air-vapor compressor application. The criteria and characteristics of the design have to be justified in order to come out with the best designs.

3. Learn to use ANSOFT Maxwell software, ANSYS

Generally, ANSYS software, ANSOFT Maxwell is a software that allows the computer model construction of structures, machine components or system in 3-D or 2-D dimensions. ANSYS is used to draw and design the electrical machine, as well as simulate the design especially to see the distribution of air-gap and magnetic flux. For the project, the author use ANSYS software to find the distribution of air-gap and magnetic flux in the linear motor design. Besides, ANSYS also can be use to analyze the back EMF produce by the stator and rotor. The author has to learn how to use ANSYS software to analyze them and finally choose one best design for the reciprocating air-vapor compressor.

4. Selection of one best design

By using the ANSOFT Maxwell software, ANSYS, each of the proposed design must be analyzed regarding of their air-gap distribution, air-gap flux density, back EMF and flux linkage distribution. It is important to ensure that the designs are working at its best performance with higher efficiency. After the results are analyze, the author selects the best design of the reciprocating air-vapor compressor application. The chosen design should be verified and justified.

1.4 CONCLUSION

From the fact mentioned in this chapter, there are higher energy consumption and energy demand all over the world. This is mainly due to the urbanization and the developed industrial sector. For the household appliances, refrigerator is one of the major energy consumption at home. The reason behind this problem is because a conventional refrigerator uses an induction motor to drive a reciprocating pump through a crank. The overall performance of compressor system is affected because of the lower efficiency of the induction motor.

Therefore, a direct drive linear motor has been introduced to replace the induction machine. The best design of linear motor will determine the performance of the reciprocating air-vapor compressor. Before choosing the linear motor design, the author needs to study the various types of linear motor topologies to predict the best performance and efficiency of the reciprocating air-vapor compressor application. These studies will be discussed in the next chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter illustrates the literature review on the various topologies and technologies of the linear machine such as, linear synchronous machine, linear induction machine, linear DC machine and linear permanent magnet machine. The characteristics, advantages and disadvantages for the linear machines are identified. After studies most of the linear machine technologies, a suitable machine will be chosen for the air-vapor compressor application. This chapter also discussed about the various topologies for the chosen linear machine to identify the characteristics needed for the air-vapor compressor application. Finally, the best three designs are proposed for the linear motor air-vapor compressor based on the literature reviews.

2.2 BASIC THEORY OF LINEAR MOTOR

Briefly, as illustrated in Fig. 1.5, a linear motor can be obtained by a process of cutting and unrolling a rotary induction motor [4]. The stator is unwrapped and laid out flat and the rotor moves along the stator in a straight line. Linear motor produces motion in a straight line rather than rotational motion. Fig. 1.6 shows the normal operation of motor and the linear motor operation [8].

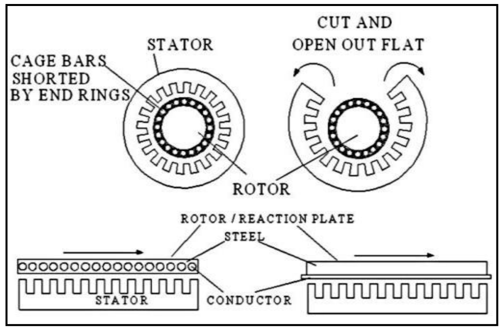


Fig. 1.5 Development of linear induction from rotary motors [8]

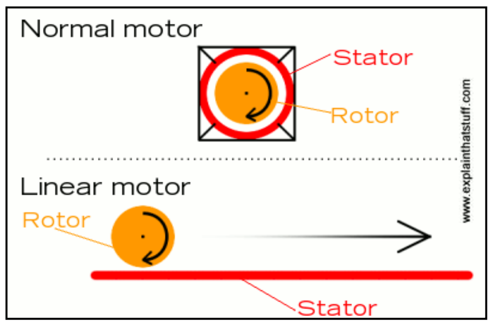


Fig. 1.6 Operation of normal motor and linear motor [9]

In general, a linear machine that consists of unrolled stator and rotor will produce a thrust force when there is an interaction between two magnetic fields. The interaction of the two magnetic field happened when a straight current-carrying is placed in a magnetic field from a permanent magnet. The force produce is linearly proportional to the current and the magnetic field.

2.3 LINEAR MACHINE TECHNOLOGIES

The first linear electric motor was originally in the USA more than a century ago [10]. Since that time, the linear motor technologies are developed all over the world. Thus, there are various applications that apply the linear motor technologies and one of the applications is a reciprocating air-vapor compressor.

Fundamentally, there are four major of linear machine technologies which can be considered [4] as candidates for linear compressor refrigerator system, namely:

i. linear induction machines
ii. linear synchronous machines
iii. linear DC machines
iv. linear permanent magnet brushless machines

2.3.1 LINEAR INDUCTION MACHINE

Basically, for linear induction machine, the rotor voltage, which produces the rotor current and the rotor magnetic field, is induced in the rotor winding rather than being physically connected by wire [11]. As mentioned earlier, linear motor produces motion in a straight line rather than rotational motion.

The linear induction machines usually use for a large application, such as, magnet levitation, linear propulsion and linear actuator. Fig. 1.7 shows the basic schematic of linear induction motor [12].

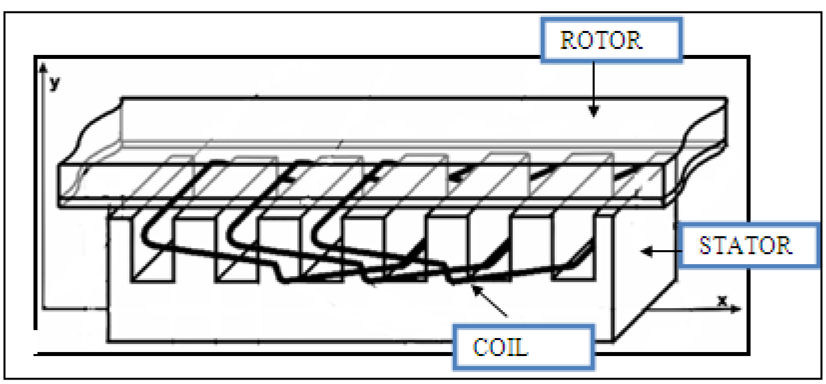


Fig. 1.7 Basic schematic of linear induction motor [12]

There are some disadvantages of the linear induction machines that may affect the performances of the air-vapor compressor. The disadvantages [13] are:

i. Poor performance at low speed
ii. Physical assembly of the stator is complex
iii. Normally used for three phase system

Since the application of linear induction machine is limited to large application and has a poor performance at low speed, thus, it is not suitable for the use of a small application of a low speed reciprocating air-vapor compressor.

2.3.2 LINEAR SYNCHRONOUS MACHINE

Generally, linear synchronous machine have been developed widely in high performance system, such as a long stroke applications [4]. The synchronous machine is running at the synchronous speed and it required more than one power supply. However, the linear synchronous motor with permanent magnet motor also can be apply for short-stroke linear motor actuator in robotics and machine tool [14].

Fig. 1.8 shows one of the applications of linear synchronous machine in magnet levitation transportation [15]. Linear synchronous machine provides the forward propulsion for the transport to move forward along the track.

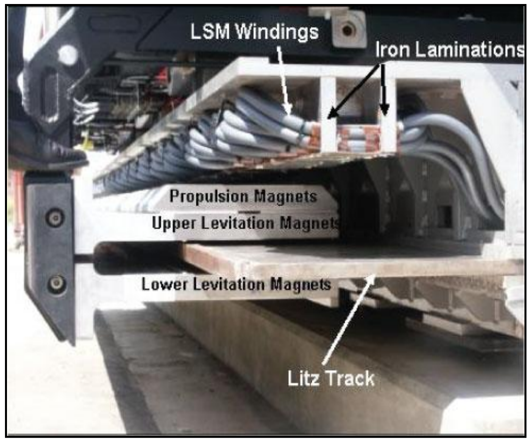


Fig. 1.8 Linear Synchronous Machine in Magnet Levitation Transportation [15]

There are some disadvantages of the linear synchronous machines that are not benefits for the air-vapor compressor [13], such as:

i. Poor performance at low speed
ii. Application is limited due to relative complexity of stator winding.
iii. Require multi-phase power supply.

Due to the disadvantages of the linear synchronous machine, it is not suitable to drive the reciprocating air-vapor compressor. Besides, the compressor system only needs one power supply.

2.3.3 LINEAR DC MACHINE

Basically, a DC motor is driven from a DC power supply. There are five major type of DC motor in general use [11], such as, the separately excited DC motor, the shunt DC motor, the permanent magnet DC motor, the series DC motor, and the compounded DC motor.

Among the types of DC motor, the permanent-magnet DC motor offer number of benefits [13]. However, the permanent magnets for DC motor cannot produce high flux density and it will results in a lower induced torque.

Due to the poor performance of the linear DC machine at low speed, it is not suitable for the high efficiency reciprocating air-vapor compressor. In addition, linear DC machine is expensive to manufacture and it also required an inverter to convert to AC supply.

2.3.4 LINEAR PERMANENT MAGNET MACHINE

Linear permanent magnet machine is preferable for the reciprocating compressor applications because it provide several benefits, such as it can produce a high force capability and high efficiency, with a low power supply [4]. The simple configuration of linear permanent magnet motor do not required field winding because the permanent magnet produces its own magnetic flux for the motor. Fig. 1.9 illustrated the basic configuration of linear permanent magnet machine with a straight movement [16].

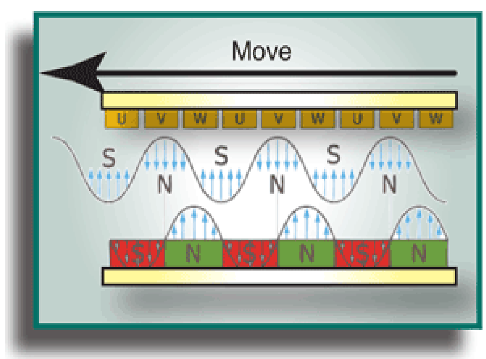


Fig. 1.9 Linear Permanent Magnet Machine [16]

For the linear permanent magnet motor design, various topologies can be considered such as, planar and tubular, slotted and slotless, and iron-cored and air-cored armature configuration. In general, the tubular topologies are preferred for a higher thrust capability compared to the planar design. It has zero net radial force between the armature and stator, no end winding and are volumetrically efficient [5]. Besides, the slotted topologies can improve the thrust force capability, while the slotless design has lower cogging force [4]. The iron-cored and the air-cored armature configuration will determine the dynamic capability of a linear motor. Higher dynamic capability will give smooth motion to the motor. In addition, the lighter moving mass also can improve the dynamic characteristics of a compressor [5]. However, there are three categories of the permanent magnet linear motor that will be discussed, namely;

i. moving-coil
ii. moving-iron
iii. moving-magnet

2.3.4.1 Moving coil

Generally, a basic structure of a moving-coil permanent magnet machine is a stationary permanent magnet, either radially or axially magnetized in the stator and a moving-coil armature winding in the rotor, as illustrated in Fig. 1.10.

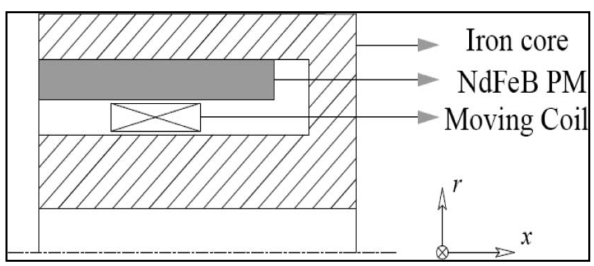


Fig. 1.10 Basic structure of moving-coil moving magnet [17]

For the basic structure of moving-coil moving magnet design, the thrust force and the generating efficiency need to be optimized. The reciprocating thrust force is also imbalance along with the current direction due to the armature reaction [17].

The improve moving-coil moving magnet design as shown in the Fig. 1.11 is proposed to enhance the thrust force and decrease the thrust ripple. The unique feature of quasi-Halbach magnetization is used because of the benefits of the axially magnetized magnets that provide a return path for the radial air gap flux [18]. Thus, the flux in the inner bore is relatively small.

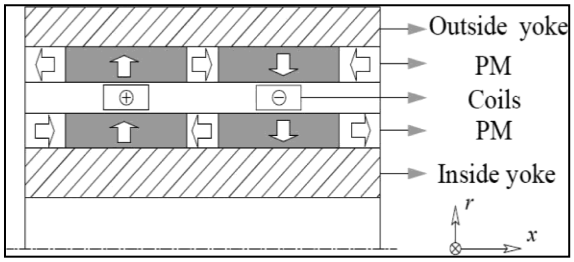


Fig. 1.11 Improved structure of moving-coil moving magnet [17]

However, moving-coil moving magnet has a few drawbacks [18], namely;

i. limited thrust capability
ii. limited flying leads to the current-carrying coil
iii. less dynamic capability as the motor power increase

According to the analysis, a moving-coil permanent magnet design is not suitable for a low power reciprocating linear motor for a refrigerator compressor system.

2.3.4.2 Moving iron

"Moving-iron permanent linear motors become a simpler design since it always only required to have uni-directional force capability and use a mechanical spring to reverse the motion of the plunger when the motor is de-energized" by Taib Ibrahim [4].

Fig. 1.12 shows a basic configuration of the linear generator that is under consideration [19]. The figure illustrated a generator with a two-phase tubular device. The stator consists of permanent magnets and coils, while the moving armature is a simple salient iron-core.

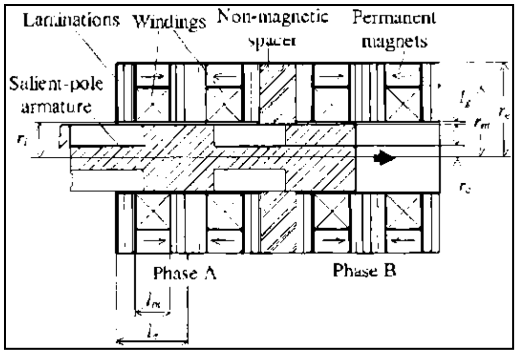


Fig. 1.12 Schematic of two-phase tubular permanent magnet generator [19]

Wang et al [18] introduced a moving-iron machine, which has a stationary magnets and stator coil, as illustrated in Fig. 1.13. The energy conversion of moving-iron is much inferior compared to the moving-magnet machine topologies, and their thrust per moving mass is even lower. It would make the machine difficult to facilitate resonant operation at the supply frequency with minimum spring stiffness.

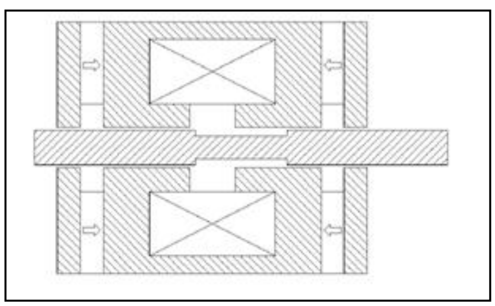
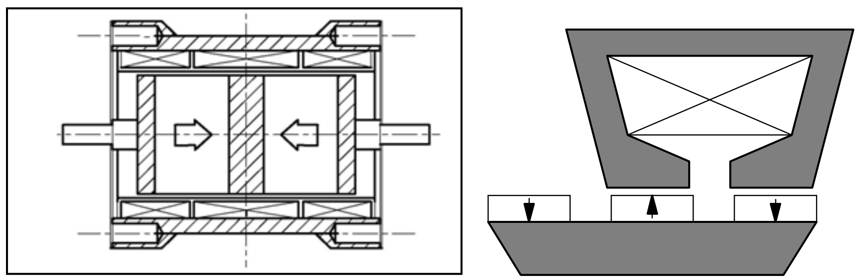


Fig. 1.13 Moving-iron topologies [18]

However, moving-iron topologies have a few disadvantages such as, heavy moving mass, which can reduce the dynamic capability of the motor and relatively low thrust force capability. Therefore, moving-iron topologies are not suitable for a low power reciprocating linear motor of a refrigerator compressor system.

2.3.4.3 Moving magnet

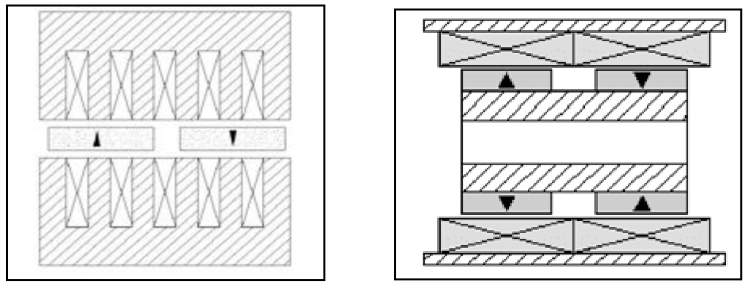
Moving-magnet motor has various topologies such as, planar or tubular, slotted or slotless stator, and also different type of magnet configuration. The magnet configuration can be axially or radially magnetized [15], as illustrated in Fig. 1.14 (a) and (b). The configuration of magnets can reduce the back-iron thickness and improve the movement of the linear motor.



a) Axially magnetized [18]　　　　b) Radially magnetized [4]

Fig. 1.14 Linear moving magnet motor

Fig. 1.15 (a) and (b) shows the example of slotted and slotless stator design for permanent-magnet linear motor [18]. The slotted topologies can improve the thrust force capability, while the slotless design has lower cogging force between rotor and stator [4]. Thus, by employing a slotted stator and higher remanence of permanent magnet, the force capability can be improve.



a) Slotted design (b) Slotless design

Fig. 1.15 Stator design [18]

Furthermore, by using the Halbach magnetized moving-magnet, as shown in Fig. 1.16, the performance of a slotted tubular motor could be improve [18]. Compared with the conventional moving-magnet linear motor topologies, Halbach magnetized armature motor can reduce moving mass, which will increase their dynamic capability. The permanent-magnet material is better utilize, which results in a higher gap flux density for a given grade and volume of magnet.

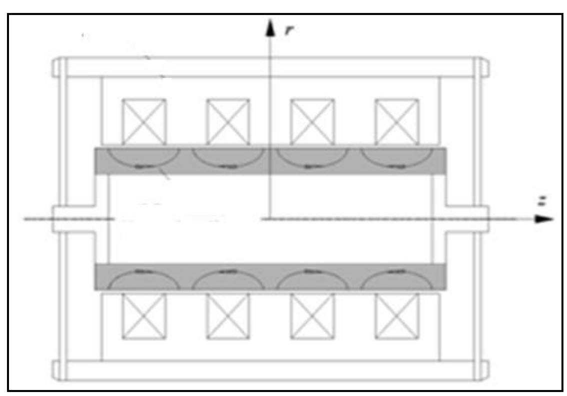


Fig. 1.16 Halbach magnetized moving-magnet [18]

Since the Halbach magnetized cylinder is difficult to manufacture [18], the machine topologies with a quasi-Halbach magnetized is more preferable, as illustrated in Fig. 1.17. The unique feature of the quasi-Halbach magnetized is the axially magnetized magnets effectively provide a return path for the radial air-gap flux easily. Hence, the flux of the inner bore is quite small. Thus, the use of a very thin ferromagnetic tube or a non-magnetic tube to support the magnet will yield a light moving armature [20]. This is conducive to improve dynamic capability and lower spring stiffness for a linear reciprocating compressor. This will also improve the thrust force capability of the linear motor.

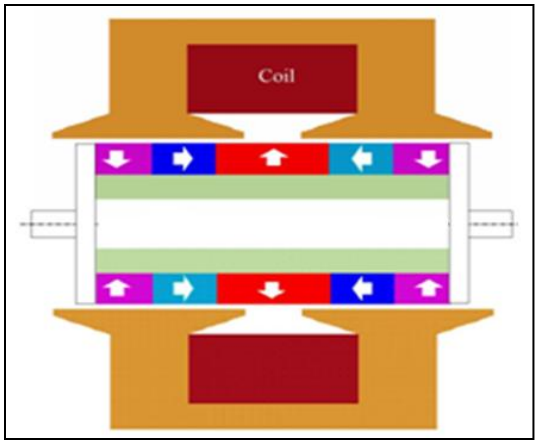
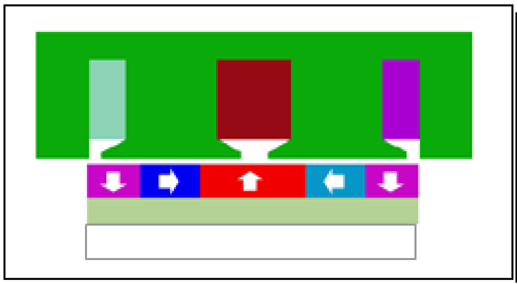
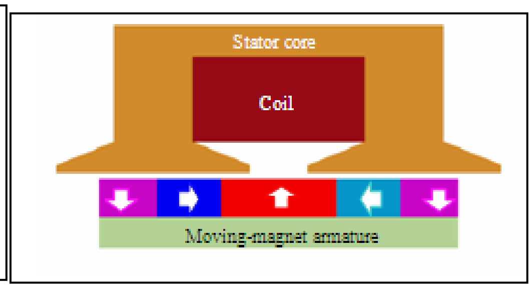


Fig. 1.17 Quasi-Halbach magnetized moving-magnet [14]

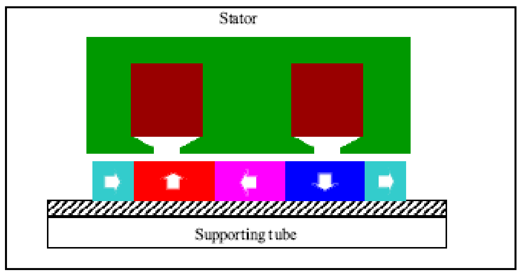
Wang et al [22] study on three variants of short stroke, tubular motor with quasi-Halbach magnetization, as shown in Fig. 1.18 (a), (b) and (c). The three designs have a different number of slots. The number of slots will affect the winding inductance as well as winding factors. Both the winding factors and winding inductance are also depends on the armature reaction field, either homopolar or bipolar.

The back-iron thickness can be reducing by employing an appropriate magnetization pattern, which results in a lower moving mass. From the three motor designs, the motor with a single stator coil has a higher thrust capability than that of the three-slot, distributed motor winding [22].





a) Three slotted (b) Single slotted



(c) Double slotted

Fig. 1.18 Quasi-Halbach magnetized with different number of slots [22]

A conventional design of slotless stator with an axial magnetized [23], as illustrates in Fig. 1.19 (a), results in higher specific thrust force capability compared to other stator topologies. Whilst, Fig. 1.19 (b) shows an improved designs of slotless stator with an axial magnetized, which results in a better utilization of the permanent magnet and a higher acceleration capability when a moving magnet armature is employed.

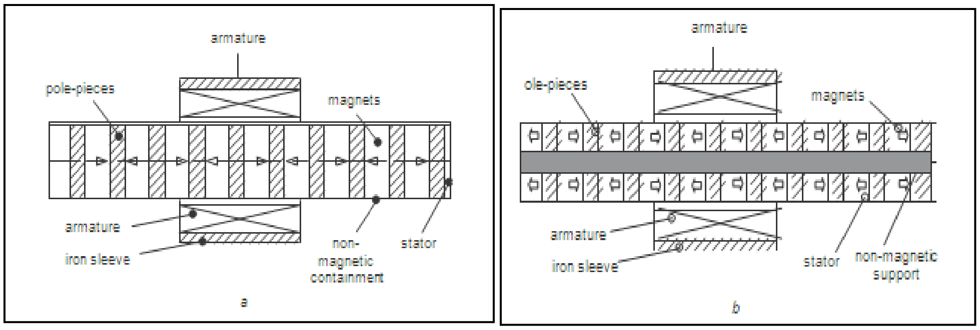
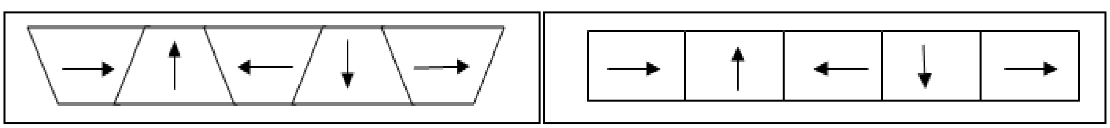


Fig. 1.19 Conventional and improved slotless stator design with an axial magnetized tubular permanent magnet topologies [23]

A further improvement for higher thrust force capability can be achieved by employing a trapezoidal shaped magnet, as illustrated in Fig. 1.20 (a). Fig. 1.20 (b) shows the quasi-Halbach magnet array with rectangular magnet, which always been used in the moving-magnet linear motor topologies. The used of quasi-Halbach magnetization pattern have a number of benefits, such as, it result in very low electromagnetic force ripple and it is possible to achieve zero cogging force after being optimized [24].



a) Trapezoidal shape magnet (b) Rectangular shaped magnet

Fig. 1.20 Different pattern of quasi-Halbach magnetization

From the number of studies earlier, permanent magnet linear motor is able to perform well at low speed and suitable to used for low power reciprocating application. In addition, permanent magnet linear motor provides higher efficiency, as well as higher thrust force capability [13]. Furthermore, the moving-magnet linear motor is more reliable and rough because of the nonexistence of flying leads to the armature [4]. Hence, the moving-magnet linear motor is appropriate for higher duty application, especially for air-vapor compressor application.

2.4 PROPOSED DESIGNS

After the studied on the various types of linear machine topologies and technologies, the best designs for the reciprocating air-vapor compressor are determined. The most significant criteria for the design of linear motor for reciprocating air-vapor compressor are based on their force capability, higher efficiency, simplicity and cost-effectiveness. From the analysis, a single-phase, moving-magnet, tubular linear motor with a slotted stator is considered to be most preferable design for the air-vapor compressor.

In addition, Table 1 below is the three types of permanent magnet's properties that will be considered for the air-vapor compressor application [25]:

Table 1: Properties of Permanent Magnet

Types of magnet	Properties
Alnico	• High magnetic remanence flux density, low temperature coefficients. • Allow a high air gap at high temperature. • Easy to magnetize and demagnetize. • Sometimes protected from armature flux – additional mid steel pole
Rare Earth	• Minerals mixed compound • NdFeb, better magnetic properties • Higher remanence magnetic flux. • Expensive and limited
Ferrite	• High coercive force • Lower remanence magnetic flux • Very high electric resistance – no eddy current losses • Economic advantages

The main characteristic of the proposed designs for the air-vapor compressor application are:

- Tubular moving-magnet linear motor.
- Single-phase slotted stator with chopped top-edge
- Radially and Quasi-Halbach magnetized pattern.
- Consists of non-ferromagnetic tube.

Thus, three designs have been selected for the further studies, which are:

1. DESIGN A: Radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel, as shown in Fig. 1.21
2. DESIGN B: Radially magnetized slotted linear motor, with the trapezoidal magnet arrangement separately with mild steel, as shown in Fig. 1.22
3. DESIGN C: Quasi-Halbach slotted linear motor, as shown in Fig. 1.23

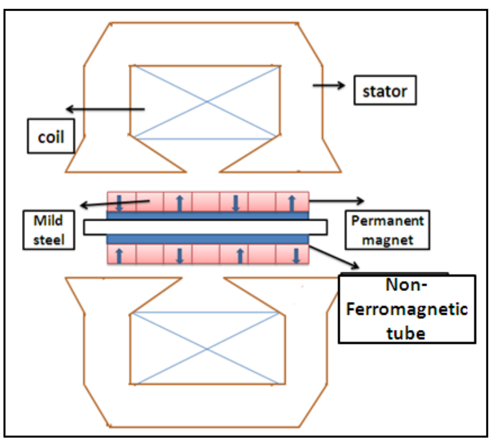


Fig. 1.21 Radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel

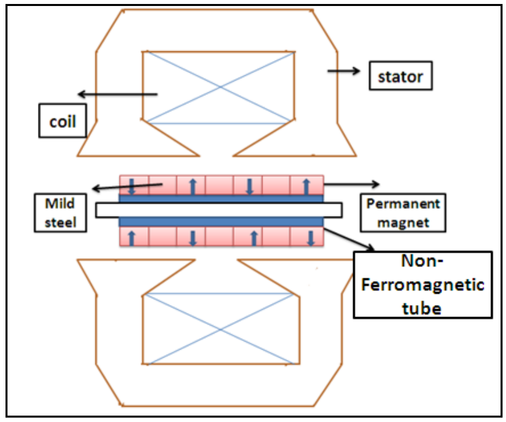


Fig. 1.22 Radially magnetized slotted linear motor, with the trapezoidal magnet arrangement separately with mild steel, as shows in Fig. 1.21

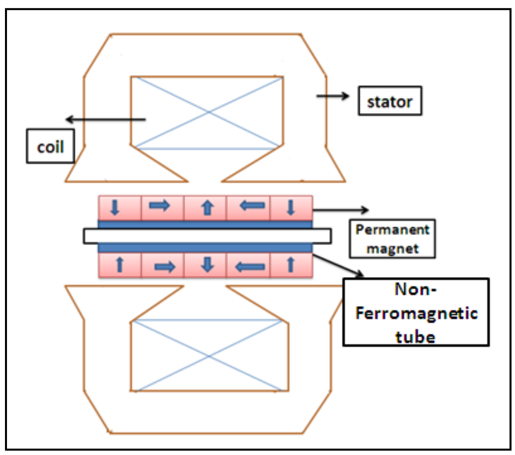


Fig. 1.23 Quasi-Halbach slotted linear motor

Generally, the tubular moving-magnet linear motor is selected for the three designs because it provides higher efficiency. The advantages of the tubular configuration are, it does not have end winding and have zero net radial force between the armature and stator [5].

Besides, the single-phase slotted stator is chosen compared to the three-phase slotted stator due to the easy manufactured and higher thrust force capability that benefits the air-vapor compressor application. In addition, the stator is manufactured from mild steel. The top edge of the stator is taken out because it will not affect the moving of flux between rotor and stator. Therefore, the volume of the stator can be reduced. Since the cogging force for slotted stator is quite high, the end effect of the stator’s tooth need to be optimize in order to reduce the cogging force.

For design A and B, radially magnetized pattern is chosen due to the direct flux linkage between rotor and stator. It caused a strong air-gap and able to produce high thrust capability. The leakage flux is relatively small and it can be support by the non-ferromagnetic tube. Besides, the quasi-Halbach magnetized pattern (design C) has been chosen for the design 3 because of its unique feature, which the axially magnetized magnets effectively provide a return path for the radial air-gap flux easily [21]. Furthermore, the type of permanent magnet used in the designs is not decided yet. There are several factors that need to be studied for the type of permanent magnet. The type of permanent magnet for the three designs will be chosen after their air-gap flux distribution are analyzing by using ANSYS software.

The used of mild steel separately with the permanent magnet for design A and B can significantly reduce the volume of permanent magnet of the linear motor. Although the ferromagnetic support tube can increase the efficiency of the linear motor, but it is not much different by using the non-ferromagnetic support tube. Therefore, the non-ferromagnetic support tube will be used for the three proposed designs.

All the preferred design will go through the complete design process in order to establish the best design for the reciprocating air-vapor compressor. Further analysis and evaluation must be carried out for each of the proposed designs by using the ANSYS software, to determine the optimum design for the reciprocating air-vapor compressor. By simulation using the ANSYS software, the distribution of air-gap, air-gap flux density, magnetic flux and back EMF of each designs can be analyze.

2.5 CONCLUSION

Various types of linear machine technologies have been reviewed and discussed such as, linear induction machine, linear synchronous machine, linear DC machine and linear permanent magnet machine. Several topologies for the linear machine technologies also have been discussed in this chapter. From the studies, linear permanent magnet machine has been chosen for the air-vapor compressor application due to its high force capability and high efficiency at low speed drive. Besides, moving magnet of linear permanent magnet is used because the advantages of its topologies like tubular or planar, slotted or slotless and others.

Three best designs have been proposed according to the criteria that were identified in this chapter. The three designs are Radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel, Radially magnetized slotted linear motor, with the trapezoidal magnet arrangement separately with mild steel, and Quasi-Halbach slotted linear motor. All the designs need to be further reviewed to ensure they are working and functioning. The project flow about the project and to analyze the designs will be introduced in the next chapter, as well as the method of using ANSYS software, ANSOFT Maxwell.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter involves the element determination to ensure this project are function and success. It involves the project flows and the characteristics of different permanent magnet remanence that are discussed in order to determine the suitable permanent magnet for the slotted linear motor machine of air-vapor compressor. Besides, the Ansoft Maxwell software, ANSYS that is used to draw and analyze the designs also will be reviewed in this chapter. Finally, this chapter will show the method of using ANSYS to analyze and generate magnetic flux for the three proposed designs.

3.2 PROJECT FLOW

Fig. 1.24 shows the project flow of designing the slotted linear motor for air-vapor compressor. For FYP 1 flows, first is the problem identification, which the author needs to identify the problem of the energy consumption of the refrigerator. The author introduces a linear motor to drive the refrigerator compressor system. Next is to conduct a literature review on various types of linear motor technologies and topologies. The author must understand the concept of linear motor and gather all the related information from journal, websites, magazines and other sources. After the studies of various types of linear motor technologies and topologies, the author comes out with the three proposed designs for air-vapor compressor application. The three designs are the tubular permanent magnet linear motor with slotted stator and different configurations of magnet.

After the proposed designs have been established, the author has to learn how to use the ANSYS software, ANSOFT Maxwell for simulation process. The analysis on flux distribution, air-gap flux density and moving force capability need to be obtained for the three proposed designs. The analyses were continues for FYP 2, where the author must get the correct preliminary results for the proposed designs. Then, the preliminary results must be discussed in detail, in order to get the best design among the three proposed designs for air-vapor compressor.

Finally, after the results have been discussed and finalized, the author can start the thesis writing on Modeling of linear permanent magnet for air-vapor compressor application.

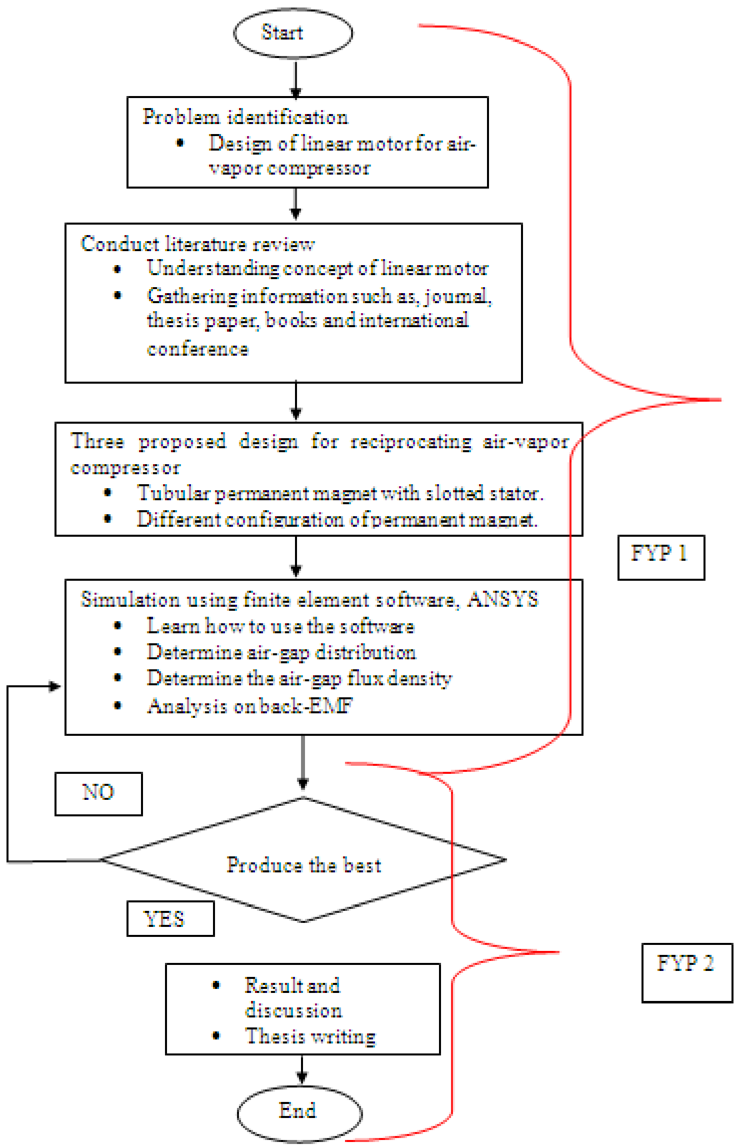


Fig. 1.24 Project flow of designing slotted linear motor

3.3 ELEMENTS DETERMINATION

In this project, a slotted linear permanent magnet for air-vapor compressor is decided to be designed. The elements to ensure this project are function and success needs to be determined and studied in details. A few studies about the important elements of the linear motor have been conducted before the three designs are proposed in chapter 2.

3.3.1 Permanent magnet

The chosen of permanent magnet is important for the three proposed designs as it will attach to the rotor part that will drive the linear motor. The permanent magnet also will determine the efficiency of the linear motor. There are two criteria in choosing permanent magnet, which are the cost and performance. These two criteria need to be balance to avoid loss.

Table 2: Magnetic field strength of permanent magnet in Tesla [13]

Permanent Magnet	Samarium Cobalt (SmCo)	Neodymium Iron Boron (NdFeB)	Alnico
μr (T)	0.8-1.1	1.0-1.4	0.6-1.4

Table 2 shows the magnetic field strength of the permanent magnet that can be considered for linear motor for air-vapor compressor. The best type of magnet will be chosen after the flux distribution for each design is obtained by analyzing using ANSYS software.

3.3.2 Arrangement of permanent magnet

The arrangement of permanent magnet is important to determine the performance of linear motor. There are three arrangement of permanent magnet that have been introduced for the three proposed designs. All the three arrangement have its own characteristic as mentioned in the literature review of chapter 2.

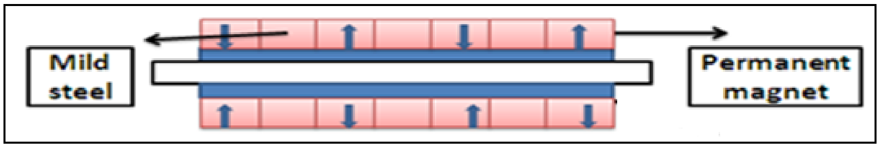


Fig. 1.25 Radially magnetized permanent magnet separated with mild steel

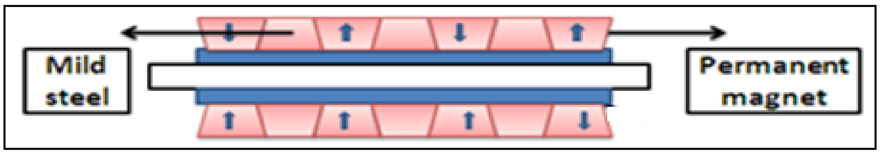


Fig. 1.26 Radially magnetized of trapezoidal permanent magnet separated with mild steel

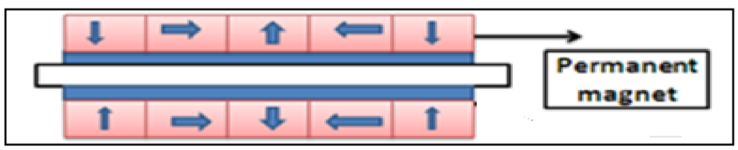


Fig. 1.27 Quasi-Halbach magnetized arrangement

Fig. 1.25, Fig. 1.26 and Fig.1.27 show the three different arrangements of the three proposed designs. Theoretically, the radially magnetized pattern and Quasi-halbach magnetized pattern give better performance for the linear motor application. However, the decision of the best design will be determine after analyzing them with the ANSYS software.

3.4 APPLICATION TOOL

ANSYS Maxwell is the premier electromagnetic field simulation software. It can be used to design and analyze 3-D and 2-D electromagnetic and electromechanical devices such as, motors, actuator and coils [26]. ANSYS software gives automated solution process where the users only need to specify geometry, material properties and the desired output. This is because it uses the accurate finite element method to solve problems. Therefore, ANSYS software will produce an appropriate, efficient and accurate mesh for solving the problem from the designs.

The three proposed designs need to be draw, validate and analyze by using ANSYS software in order to get the air-gap flux distribution, air-gap flux density, mesh operation and the force of the linear motor.

3.4.1 The procedures to design the linear motor by using ANSOFT Maxwell Software

First, open or access the ANSYS software. Then, the user need to choose the Maxwell 2-D Design to open new project. Set the solution type by choosing Cartesian, XY with Transient magnetic mode.

Second, create model by drawing the three proposed designs with the right dimensions and name all the design parts. Assign the material for each part of the designs, for example, the material for coil is copper. Create a boundary or region for the designs and set it as Balloon1. Next, set the excitation for the designs by insert the number of conductor inside coil, add winding and add coil to the winding. Eddy effects are assigned after the setting of excitation.

After that, create the Analysis Setup by filling the General tab and Save Field tab. The stop time and time step need to be filled inside both tabs. The mesh operation must be assigned because it is not automatically created for transient solver.

For the motion setup, the user must create one region for the moving part which is a rotor. Automatically, the band is assigned for the rotor. Then, the user must filled the details inside the Type tab, Data tab and Mechanical tab for the motion setup.

After done all the setup, it must be validate and analyze for a solution process. The process might take few minutes before the results are obtained. Finally, the result of air-gap flux distribution, air-gap flux density, plot mesh and the graphs can be reviewed. The user can analyze the designs by using the results obtained.

3.5 CONCLUSION

In conclusion, the important key elements of the project such as the permanent magnet characteristics and arrangements have been reviewed. These elements determination are the important criteria considered in designing the linear motor for air-vapor compressor. Since all the permanent magnet such as, NdFeB, Smco, Alnico and Ferrite has its own characteristics, therefore, the designs with different arrangement need to analyze by using ANSYS software to get the results of air-gap flux distribution. The type of permanent magnets for the three proposed designs will be chosen after the results are obtained. This result will be discussed in the next chapter of the thesis.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter illustrates results and discussion of linear motors which are proposed in Chapter 2. First, the plot mesh operation for each proposed designs are analyzed. Then, the type of permanent magnets is compared according to its remanence and air-gap flux distribution in order to choose the best magnet for the three proposed designs of air-vapor compressor linear motor. Next, the graphs of air-gap flux density and moving force for the three designs are obtained and analyzed. Finally, the results will be discussed and compare to choose one best design for the air-vapor compressor linear motor.

4.2 COMPARISON OF PLOT MESH FOR THE THREE DESIGNS

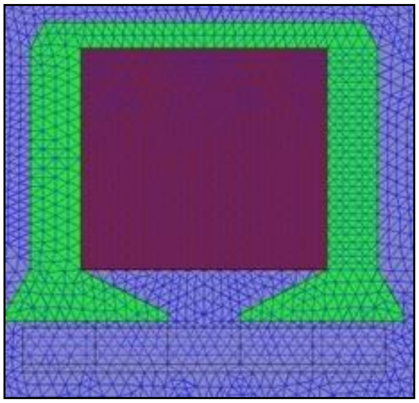
Plot mesh for the three designs is obtained to analyze. Fig 1.28 (a), (b) and (c) shows the plot mesh of the three designs which are radially rectangle magnetized pattern (Design A), radially trapezoidal magnetized pattern (Design B) and quasi-halbach magnetized pattern (Design C).

There are three types of mesh operation:

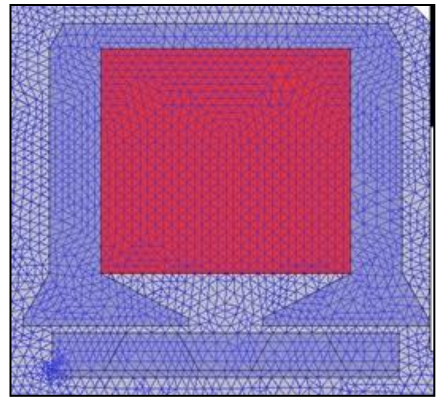
1. On Selection is applied on the surface of the object

2. Inside Selection is applied through the volume of the object

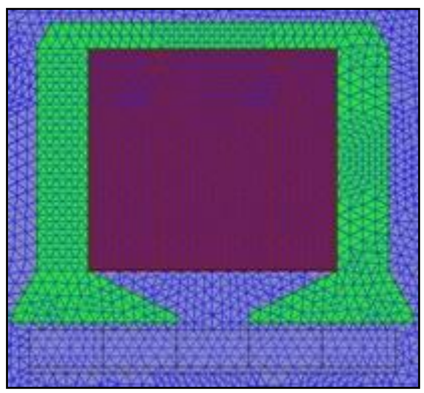
3. Surface approximation is applied to set fecating guidelines for true surface objects



(a) Radially Rectangle Magnetized pattern



(b) Radially trapezoidal magnetized pattern



(c) Quasi Halbach magnetized pattern

Fig.1.28 Plot Mesh

The plot mesh is important in designing using ANSYS software to ensure the right calculation for the proposed designs. For the three proposed designs, the author used Inside Selection mesh operation because it is calculated through the volume of the project. The plot mesh must be small enough, so that the calculation for the project is more accurate. From the figure, the plot mesh for all the designs is relatively small. Therefore, the calculation involve the designs will be more accurate as compared to the bigger plot mesh, but the time for simulation will be longer.

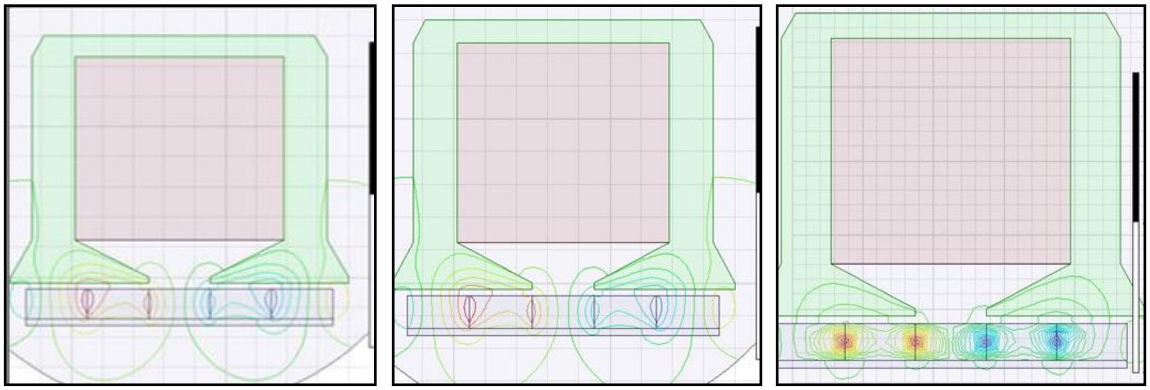
4.3 PERMANENT MAGNET DETERMINATION AND OPEN FLUX DISTRIBUTION

There are three permanent magnets that have been considered for the proposed designs which are, Samarium Cobalt (SmCo), Neodymium Iron Boron (NdFeB) and Alnico. Table 3 shows the comparison of magnetic performance of permanent magnets.

Table 3: Comparison of magnetic performance of permanent magnets [13]

Magnet	μr (T)	*Hci* (kA/m)	BHmax (kJ/m^3)	Tc (˚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

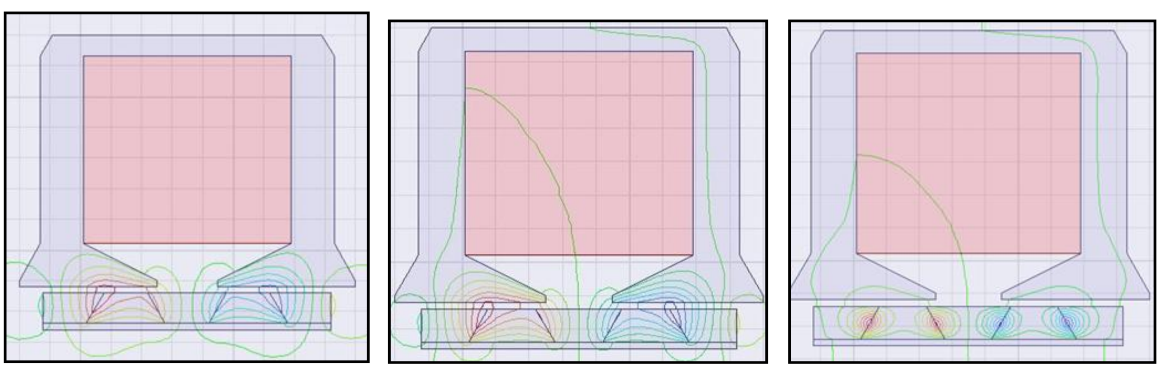
The first design of linear motor for air-vapor compressor is a radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel (Design A). Fig. 1.29 shows the open-circuit flux distribution for three types of magnet, which are, Samarium Cobalt (SmCo), Neodymium Iron Boron (NdFeB) and Alnico.



a) SmCo b) NdFeB c) Alnico

Fig. 1.29 Open-circuit flux distribution of the Radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel

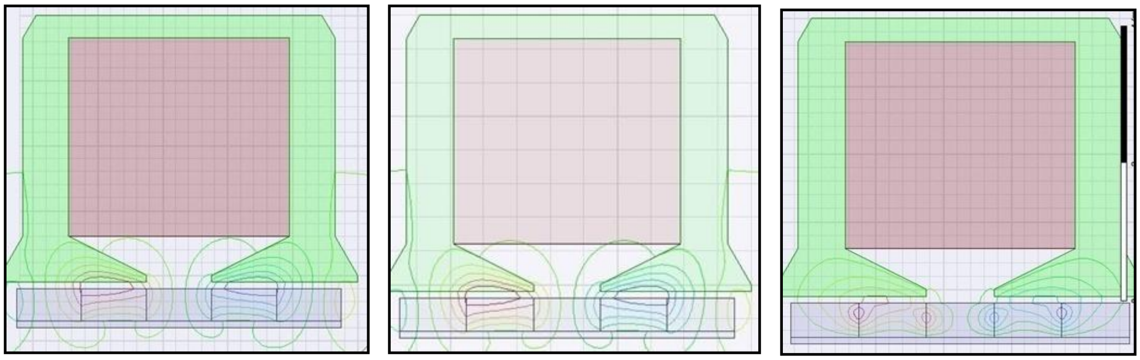
The second design of linear motor for air-vapor compressor is a radially magnetized slotted linear motor with the trapezoidal magnet arrangement separately with mild stee l (Design B),. Fig. 1.30 shows the open-circuit flux distribution of the three magnets.



a) SmCo b) NdFeB c) Alnico

Fig. 1.30 Open-circuit flux distribution of the Radially magnetized slotted linear motor, with the trapezoidal magnet arrangement separately with mild steel

The third design of linear motor for air-vapor compressor is a Quasi-Halbach slotted linear motor (Design C). Fig. 1.31 shows the open-circuit flux distribution for the three types of magnet.



a) SmCo b) NdFeB c) Alnico

Fig. 1.31 Open-circuit flux distribution of Quasi-Halbach slotted linear motor

NdFeb and SmCo are the rare-earth magnet which produce high magnetic field with less mass. They are limited and quite expensive as compared to Alnico. However, Alnico produce smaller magnetic field. It might not strong enough to drive the air-vapor compressor linear motor. Table 3 illustrated the magnetic field comparison of the three permanent magnets. From the table, SmCo and NdFeB have better performance because they have higher magnetic field which is around 0.8T to 1.4T. Alnico usually has lower magnetic field which is 0.6T

In addition, the figures show that the flux is equally divided between magnets and stator for all the types of magnets. The flux distribution shows connection between magnets (moving part) and stator (stationary part). If the flux linkage between magnets and stator are much, so the magnets are strong to run the motor. From the figures, SmCo and NdFeb magnets have similar flux distribution. The flux linkage between magnets and stator for both magnets are many as compared to Alnico. It shows that SmCo and NdFeB are stronger to run the motor than Alnico. From the comparisons of magnetic flux strength, coercive force, and flux linkage distribution, SmCo and NdFeB are considered for the compressor. Since NdFeB magnetic field strength is the highest,so, it is strong enough to drive the compressor. Therefore it is chosen for the air-vapor compressor linear motor with 1.1T.

4.4 COMPARISON OF MAGNETIC FLUX DENSITY FOR THREE PROPOSED DESIGNS

Fig. 1.32 shows the magnetic flux density for the design A. The highest value of the magnetic flux density is 0.37T.

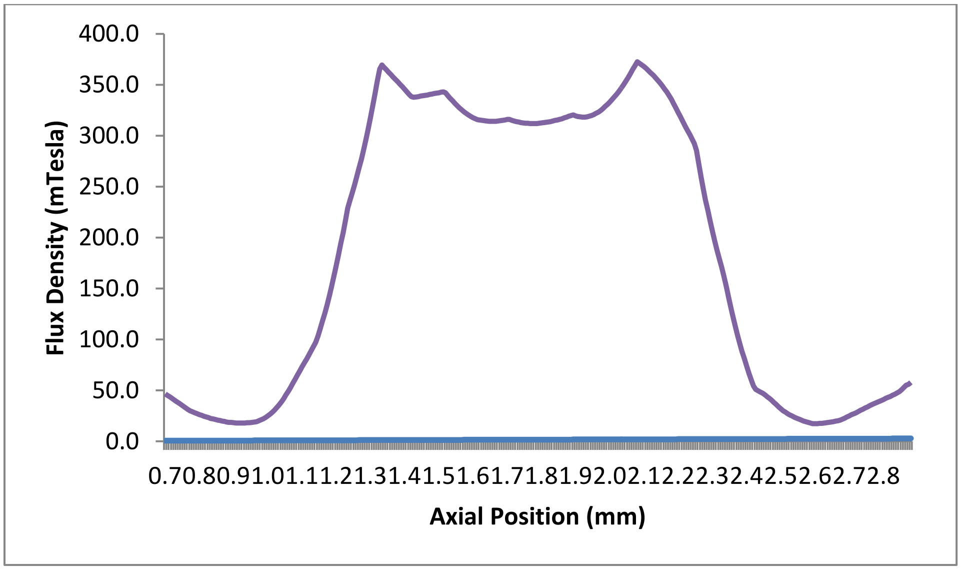


Fig. 1.32 Magnetic flux density for Design A

Fig. 1.33 shows the magnetic flux density for design B. From the graph, design B is able to reach 0.8T. The dropping point at the center is due to the slotting effect of the slotted linear motor.

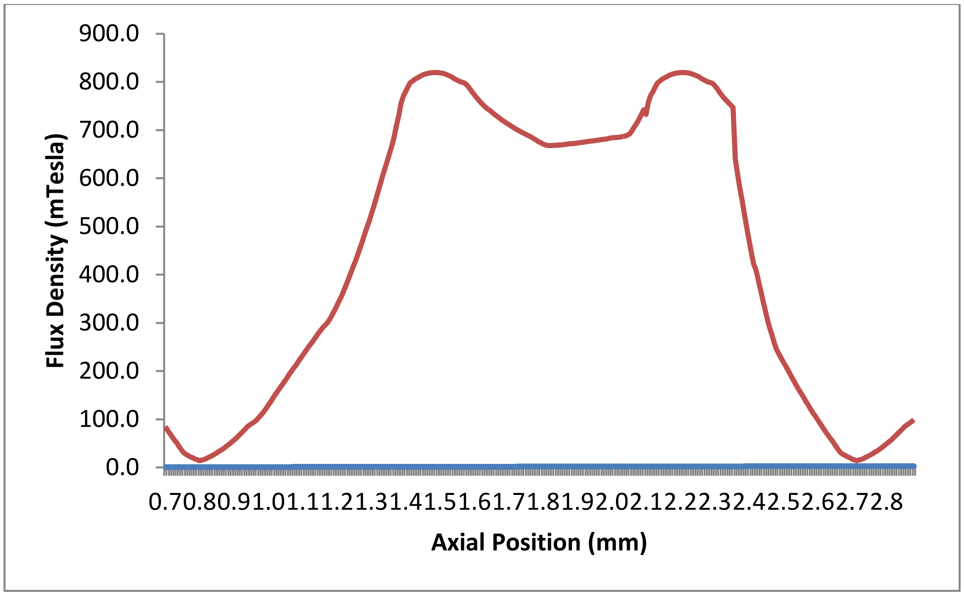


Fig. 1.33 Magnetic flux for Design B

Fig. 1.34 illustrates the magnetic flux density of design C. It is able to reach until 1T for the highest value. There is also zero value for air-gap density at some distances. The dropping point indicates the axially arrangement of permanent magnet where it is transferring the air-gap flux to the radially arrangement of permanent magnet [13].

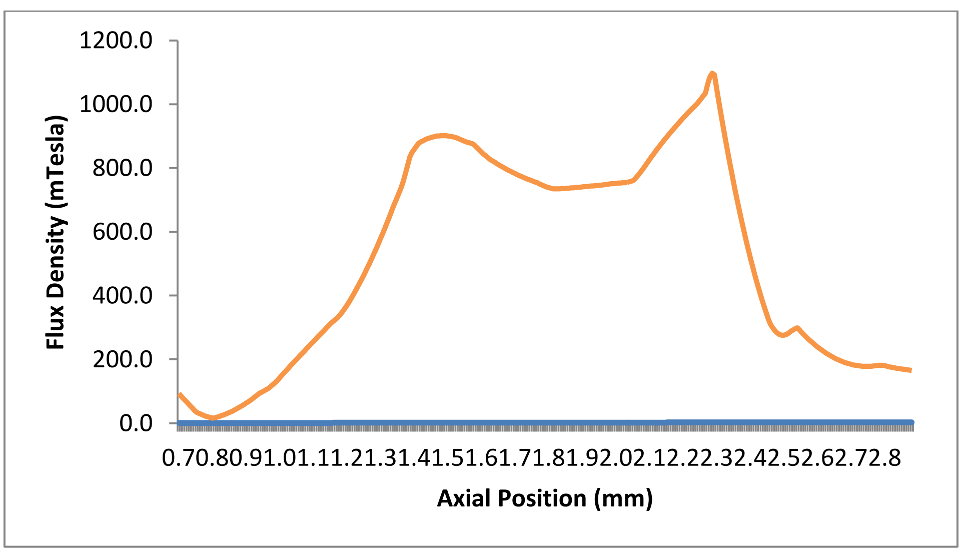


Fig. 1.34 Magnetic flux density for Design C

Fig. 1.35 illustrates the comparison graph of magnetic flux density for the three proposed designs. All the three designs have different magnetic flux density. As shown in the graph, Design C has the highest graph among others.

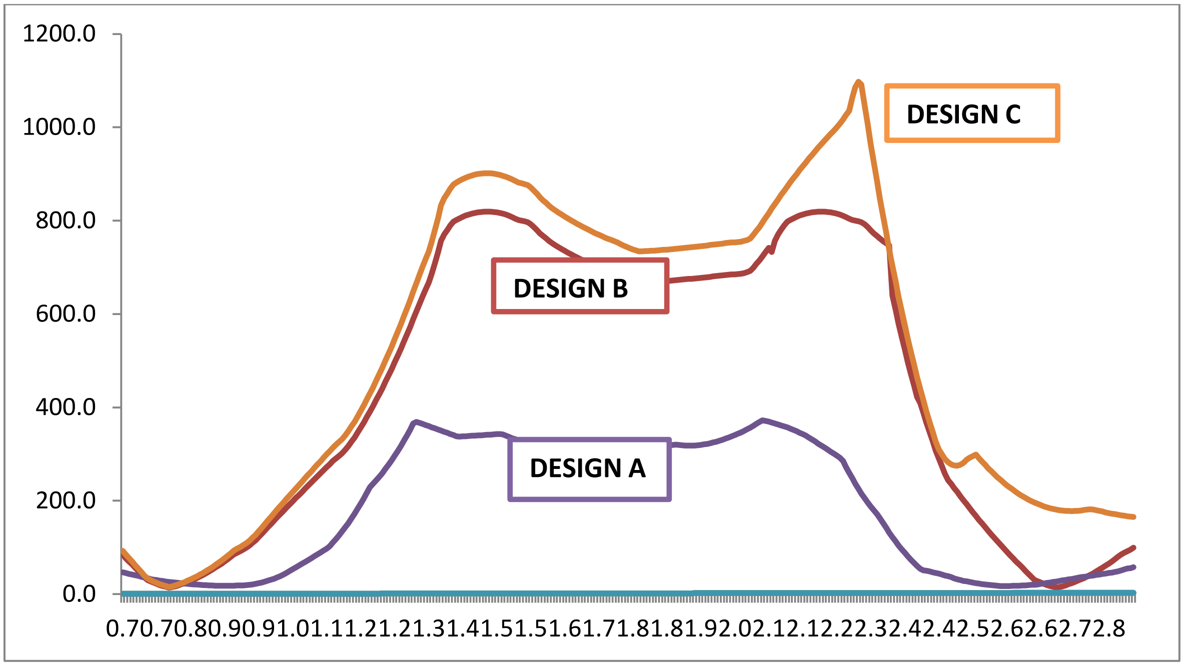


Fig. 1.35 Comparison of magnetic flux density for three designs

Table 4 shows the average value of magnetic flux density. From the table, Design B and design C have similar average value of magnetic flux density which is around 400mT to 500mT. It might result in similar thrust force capability. However, Design C has the highest average value of magnetic flux density which is 517.61mT and Design A has the lowest average of magnetic flux density which is around 1.8mT. All the graphs have a dropping point at the center that is mainly due to the slot opening of the linear motor itself. All the designs use NdFeB magnet with 1.1T. From Table 4, design B and design C have better performance than design A because of the high magnetic flux density. For design B and design C, it shows that design C is more efficient because it can reach until 517.61mT for the average. It also indicates that Design C has the strongest connection of flux between stator and rotor. The next stage is to compare the moving force of the three designs to determine the best design for air-vapor compressor application.

Table 4: Average of Magnetic Flux Density

DESIGN	Magnetic flux density (mT)
Design A	185.5
Design B	443.7
Design C	517.61

4.5 MOVING FORCE FOR THREE PROPOSED DESIGNS

Fig. 1.36 illustrates a moving force graph of the design A. The highest force obtained is 32.5N. The force is saturated from 0s to 9s. After 9s, the force reduces linearly until 29.5N.

Fig. 1.36 Moving force for Design A

Fig. 1.37 illustrates the moving force for design B. The force is saturated at the highest point which is 49N at 0s to 9.5s. After 9.5s, it reduces slowly until the point of 41.5N.

Fig. 1.37 Moving force for Design B

Fig. 1.38 shows a moving force for Design C. Design C reach its highest force of 1.5N. The force remains highest from 0s to 8.5s. The force reduces to 15N after 8.5s.

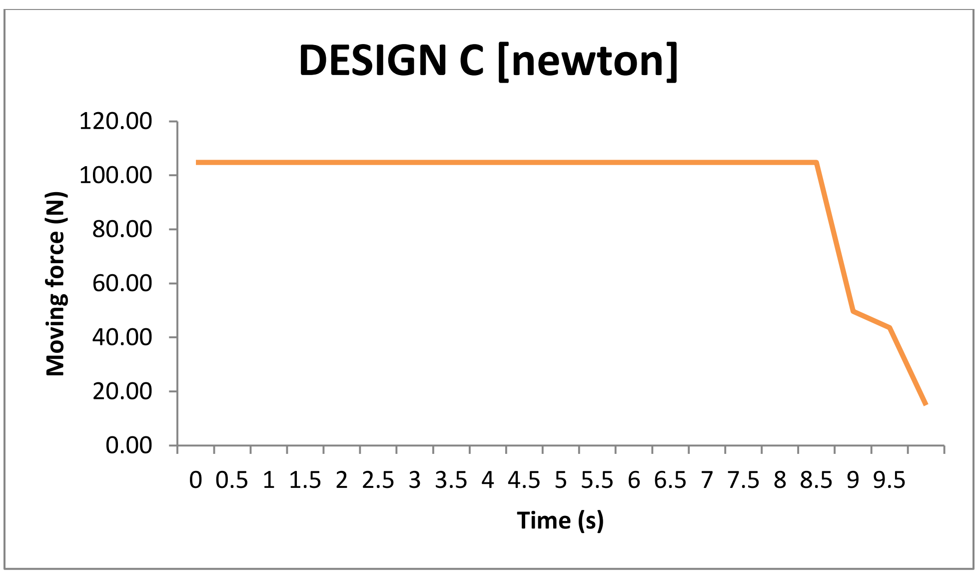


Fig. 1.38 Moving force for Design C

Fig.1.39 illustrates the combination graph of moving force for the three proposed designs. From the graph, the saturated point indicates that the force is at the maximum current supply. The graphs reduce slowly at one point because the current is changing to negative cycle and decrease linearly. From the graph, Design C has the highest peak of moving force compared to others.

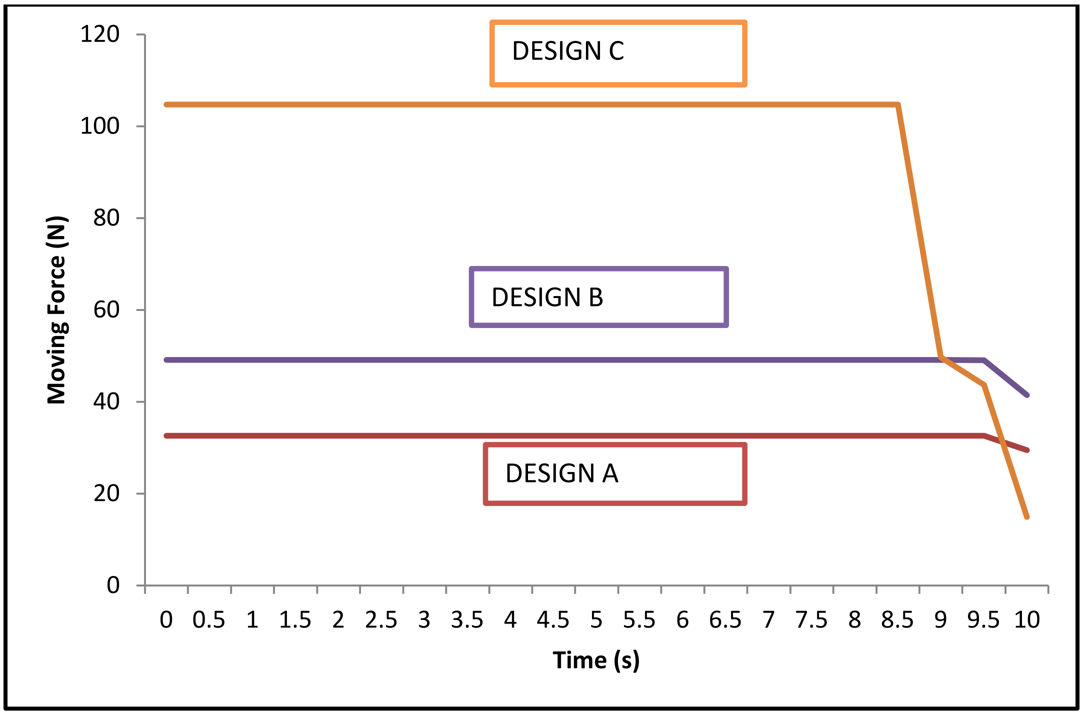


Fig. 1.39 Combination of moving force for the three designs

Table 5 shows the average value of the moving force for the three proposed designs. From the table, Design A has the highest average of moving force which is 94.91N, followed by Design B, 48.72N and Design A, 32.43N. It shows that Design A has the highest thrust force capability, while Design A has the lowest thrust force capability.

Table 5: Average of Moving Force

DESIGN	Moving force (N)
Design A	32.43
Design B	48.72
Design C	94.91

4.6 DISCUSSION

Table 6 shows the results of magnetic flux density and moving force for the three proposed designs used NdFeB permanent magnet. Theoretically, lower magnetic flux density will results in lower moving force capability. As will be observed, design A produce lower average of magnetic flux density and moving force as compared to design B and C. Design C produce the highest magnetic flux density and thrust force which are 517.61mT and 94.91N. It indicates that Design C has the highest thrust force capability and strongest air-gap flux between rotor and stator as compared to Design A and Design B.

Table 6: Results for the three designs

DESIGN	Average of Magnetic flux density (mT)	Average of Moving force (N)
Design A	185.5	32.43
Design B	443.7	48.72
Design C	517.61	94.91

By comparing the preliminary results of magnetic flux density and moving force obtained, it is proves that Design C which is quasi-halbach slotted linear motor produce the highest result. Although the highest moving force will cause higher iron loss but it can give the best performance and higher efficiency. Therefore, design C is the best designs for air-vapor compressor application compared to Design A and Design B.

4.8 CONCLUSION

In conclusion, this chapter illustrates the reasons of choosing NdFeB permanent magnet for the designs. There are also discussion about the results comparison among three proposed designs in term of magnetic flux density and thrust force.

From the comparison results obtained, it shows that design C has the highest magnetic flux density and moving force. Meanwhile, design A, produce the lowest magnetic flux density and moving force. The preliminary results obtained shows that design C give the best performance and higher efficiency for the linear motor. Thus, it is chosen for the air-vapor compressor application.

CHAPTER 5

5.1 CONCLUSION

In conclusion, there are four types of linear machine have been studied and discussed, such as, linear induction machines, linear synchronous machines, linear DC machine, and linear permanent magnet machine. From the studies, linear permanent magnet machine has been chosen for the reciprocating air-vapor compressor due to its great performance at low speed, higher thrust force capability and also high efficiency. Furthermore, a tubular moving-magnet of linear permanent magnet with slotted stator is more preferable for the reciprocating air-vapor compressor application because it fulfilled the important criteria that should have for the compressor system.

Three designs of slotted stator with different types of permanent magnet configuration have been proposed for the reciprocating air-vapor compressor, which are radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel, radially magnetized slotted linear motor, with the trapezoidal magnet arrangement separately with mild steel, and Quasi-halbach slotted linear motor. Each design has its own characteristic and advantages for the air-vapor compressor application.

The three proposed designs have been validated and analyzed by using ANSOFT Maxwell software, ANSYS to obtained the magnetic flux distribution, magnetic flux density and thrust force. The preliminary results obtained are compared among the three designs to determine which designs perform well for the air-vapor compressor application.

From the comparison results obtained in Chapter 4, it shows that design C which is Quasi-halbach slotted linear motor has the highest magnetic flux density and moving force. Besides, design A, radially magnetized slotted linear motor, with the magnet arrangement separately with mild steel produce the lowest magnetic flux density and moving force.

From the preliminary result obtained, design C is able to give best performance and higher efficiency for the air-vapor compressor application. However, the three designs need to undergo optimization process in order to determine one best design for air-vapor compressor application.

5.2 RECOMMENDATIONS

In this thesis paper, the results of magnetic flux distribution, magnetic flux density and thrust force for the three proposed designs are compared. From the comparison of the results obtained, one best design for air-vapor compressor is chosen. It is really recommended to optimize certain area of the proposed designs to improve the designs. The optimization processed will give better performance and efficiency for the air-vapor compressor application.

Other than that, a prototype can be fabricated in order to test the designs and ensure that they can be applied for the air-vapor compressor. The prototype then, will be used inside the air-vapor compressor to test and the performance can be compared with the simulation results.

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