APPLICATION OF $ND_2FE_{14}B$ MAGNET IN THE LINEAR GENERATOR DESIGN

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ABSTRACT

A study on the application of the $Nd_2Fe_{14}B$ (Neodymium Iron Boron) magnet in linear generator design is carried out to evaluate the general properties and characteristics of various types of permanent magnets and the right selection of permanent magnet for generator application. $Nd_2Fe_{14}B$ permanent magnet is selected for this application due to several factors that have been considered. Four major factors in selecting the appropriate permanent magnet for linear generator are their magnetic properties, corrosion resistance, material cost and maximum operating temperature, have been emphasized. $Nd_2Fe_{14}B$ permanent magnet plays an important role to provide a magnetic field source for the linear generator. An electromagnetic analysis has been performed to analyze the overall generator design and to determine the components' parameters of the generator. The evaluation of effect of temperature on the electromagnetic properties of the $Nd_2Fe_{14}B$ permanent magnet was carried out that leads to thermal design consideration of a linear generator.

***Keywords*:** *$Nd_2Fe_{14}B$, linear generator, electromagnetic, finite element, simulation.*

INTRODUCTION

Permanent magnets are widely used in a variety of industrial applications especially in designing sensors, motors, generators and actuators. Stronger permanent magnet types were introduced in the 1970's and 1980's. These magnets became known as the rare earth family of magnets since they were made of rare earth elements that are from samarium or neodymium. Rare earth magnets made it possible to make some devices both smaller and more powerful at the same time [1]. A revolution in permanent magnetic materials commenced about 1970 with the introduction of the Samarium Cobalt (SmCo) family of hard magnetic materials. This revolution accelerated recently with the discovery of a new generation of rare earth magnets in the 1980's based on neodymium, iron and boron with even higher magnetic energy densities than SmCo and with an anticipated lower cost [2].

The invention of the generation of the rare earth permanent magnetic material caught the attention of the world for the cost of the production of $Nd_2Fe_{14}B$ is much decreased while the magnetic property prominently increased. It is getting to replace the traditional magnet of Ferrite, AlNiCo and SmCo in many applications [3,4]. In the industry, $Nd_2Fe_{14}B$ commonly abbreviated as NdFeB which mainly consists Neodymium, Iron and Boron. It has excellent properties of high remanence, coercivity, and maximum energy compares to other class of permanent magnets.

For automotive and stand-alone (standby or remote) generator applications, the permanent magnets are the most important elements to produce required output voltage and power. Higher energy permanent magnets allow higher efficient linear generator to be produced. Figure 1 illustrates the principle of the linear generator with a free-piston combustion engine.

The generator consists of a stator, copper coils and a linear translator; which carries a set of radially magnetized permanent magnet. $Nd_2Fe_{14}B$ magnet is chosen for this application because this magnet has the highest magnetic property among other permanent magnets. Although this requirement satisfies the generator design, the material cost and corrosion resistance aspects should be considered and the maximum operating temperature for the permanent magnet should be observed to maintain its physical, mechanical and magnetic properties[5,6]. Figure 2 shows the prototype of linear generator, developed in University of Malaya, Malaysia.

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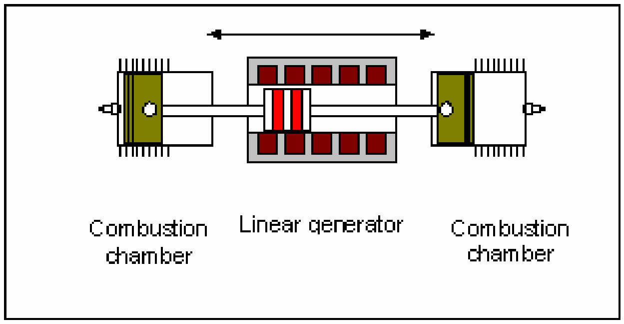

Figure 1: Linear generator with a free-piston engine.

Figure 2: Prototype of linear generator

SELECTION OF PERMANENT MAGNET

The selection of permanent magnet is the most important aspect that needs to be considered in generator design. In order to select the appropriate permanent magnets for the linear generator, four major factors are emphasized;

a) magnetic properties,
b) corrosion resistance,
c) material cost and
d) maximum operating temperature.

A good permanent magnet should produce a high magnetic field with a low mass, and should be stable against the influences which would demagnetize it. The desirable properties of such magnets are typically stated in terms of the remanence and coercivity of the magnet materials [7].

There are four classes of modern commercialized permanent magnets which each of them based on their material composition and have their own magnetic properties. These classes are $Nd_2Fe_{14}B$, SmCo, Ferrite and AlNiCo. $Nd_2Fe_{14}B$ and SmCo magnets are classified as the rare earth permanent magnets. Rare earth permanent magnet produces the largest magnetic flux with the smallest mass. Table 1 shows the comparison between four types of the permanent magnet materials [8].

A rare earth permanent magnet, $Nd_2Fe_{14}B$ is chosen based on a number of considerations especially in terms of producing high energy product. The physical, mechanical and magnetic properties of the magnet such as thermal conductivity, specific heat, electrical resistivity and magnetic flux density which are affected by temperature are investigated. $Nd_2Fe_{14}B$ magnet is selected due to its high energy at its maximum operating temperature.

Table 1: Permanent magnet material comparison

	Lowest	Low	High	Highest
Cost	Ferrite	AlNiCo	$Nd_2Fe_{14}B$	SmCo
Energy	Ferrite	AlNiCo	SmCo	$Nd_2Fe_{14}B$
Operating Temperature	$Nd_2Fe_{14}B$	Ferrite	SmCo	AlNiCo
Corrosion Resistance	$Nd_2Fe_{14}B$	SmCo	AlNiCo	Ferrite
Resistance to Demagnetization	AlNiCo	Ferrite	$Nd_2Fe_{14}B$	SmCo
Mechanical Strength	Ferrite	SmCo	$Nd_2Fe_{14}B$	AlNiCo
Temperature Coefficient	AlNiCo	SmCo	$Nd_2Fe_{14}B$	Ferrite

Magnetic properties

In any design, usually one or two parameters are needed to be considered for proper performance. In the aspect of magnetic properties, the most important parameters that need to be observed are remanance flux density (B_r), coercive force (H_{cb}) and maximum energy product (BH_{max}). These parameters will determine the final performance of permanent magnets. For a better performance, $Nd_2Fe_{14}B$ magnet is a good choice for a linear generator application. It offers the highest energy product compared to other permanent magnets. The strongest magnet has the highest maximum energy product (BH_{max}). For this purpose, $Nd_2Fe_{14}B$ magnet with grade N30EH is used [9].

The demagnetization curve at certain temperatures is probably the most useful design tools. It permits a reasonable estimate of performance of the magnet at any temperature [10]. Figure 3 shows the demagnetization curves for N30EH $Nd_2Fe_{14}B$ magnet at different temperatures while Table 2 shows the different values of important parameters of N30EH $Nd_2Fe_{14}B$ magnet with respect to temperature [11,12]. (Note that 1T=10kGs, 1kA/m=12.56Oe, 1 kJm^3=1/7.96MGsOe).

In this research, $Nd_2Fe_{14}B$ permanent magnet with grade N30EH is chosen that posses these important parameters:

Remanance flux density, B_r = 1.114 T
Coercive force, H_{cb} = 871 kA/m
Intrinsic force, H_{cj} = 2411 kA/m
Maximum energy product, BH_{max} = 241 kJ/m^3

Corrosion resistance

$Nd_2Fe_{14}B$ magnets are brittle but not as brittle as the SmCo types. Corrosion and oxidation resistance have been long standing objection but generally overcome with approach coatings of $Nd_2Fe_{14}B$, when designing a device especially generator. A surface coating is highly recommended for the magnets. A variety of coatings can be applied to the magnets surface to overcome the principle drawback of $Nd_2Fe_{14}B$ magnet, the tendency to corrode easily [13]. Therefore, for $Nd_2Fe_{14}B$ magnet, surface treatment method include zinc, nickel, tin, silver, gold plating, phosphor and spray epoxy resin can be used to provide good corrosion resistance for the $Nd_2Fe_{14}B$ magnets. For this design, tin is used as a special coating for magnet protective layer.

Material cost

$Nd_2Fe_{14}B$ magnet has some excellent advantages over SmCo magnet. Even though the cost of $Nd_2Fe_{14}B$ magnet is more expensive than Ferrite and AlNiCo, it is actually more economical than SmCo as stated in Table 1. Cost effective manufacturing of these magnets will play a crucial role in decreasing the cost of linear generator.

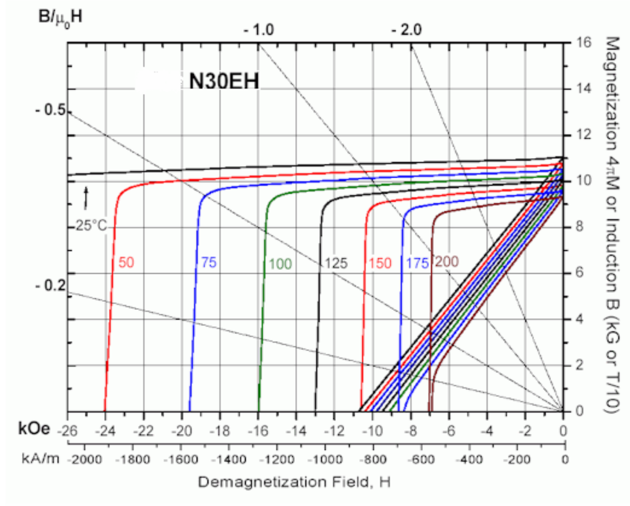

Figure 3: Demagnetization curves as a function of temperature[10]

Table 2: Important parameters of $Nd_2Fe_{14}B$ magnet with grade N30EH with respect to temperature

Temp. (^{0}C)	B_r (kGs)	H_{cj} (kOe)	H_{cb} (kOe)	BH_m (MGsOe)	B_d (kGs)	H_d (kOe)	H_k (kOe)
20	11.18	28.4	10.81	30.03	5.57	5.39	23.51
60	10.92	24.63	10.51	28.49	5.48	5.2	20.13
100	10.42	18.3	9.87	25.42	5.14	4.94	15.78
120	40.04	15.68	9.49	23.55	5	4.71	13.73
150	9.45	11.68	8.85	20.82	4.56	4.57	10.45
180	8.94	7.97	7.39	17.81	4.38	4.06	6.62
190	8.66	6.9	6.52	16.91	4.33	3.9	5.91
200	8.53	5.88	5.6	16.49	4.29	3.85	5.28

Operating temperature

Generally, $Nd_2Fe_{14}B$ magnets are more sensitive to changes in temperature (reversible temperature coefficients being around -0.13%/°C) [14]. The selection of $Nd_2Fe_{14}B$ magnets in any applications will depend on its working environment. If the magnets are used at elevated temperatures, it should have a high intrinsic coercivity (H_{cj}) [14]. For this application, magnets with moderate or high coercivity are recommended since they are used in adverse conditions such in generator.

Permanent magnet with grade N30EH grade is used due to its high maximum operating temperature and it has moderate coercivity at this working temperature. Its maximum operating temperature can achieve as high as 200^{0}C and it can also produce high BH_{max} at its working temperature.

SIMULATION AND ANALYSIS

Simulation analysis is very important in most application to evaluate the performance of the device before its prototype is constructed. For linear generator application, this analysis is used to design a model of an actual or theoretical physical system by executing the model and analyzing the execution output. Finite Element Method (FEM) software; Ansoft Maxwell® 2D and 3D are used for this application. The suitable components' dimensions and the types of materials of each component to construct the generator can be analyzed to achieve the desired output. Figure 4 shows the linear generator components and Table 3 shows the linear generator dimensions [15].

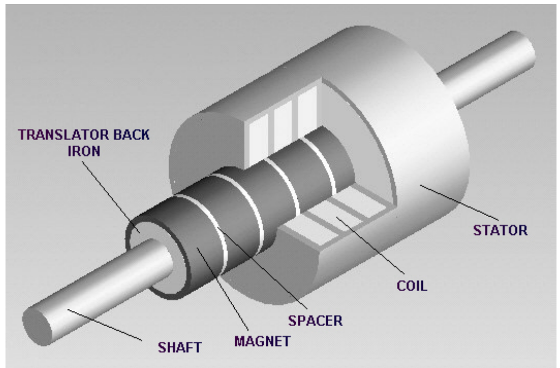

Figure 4: Linear generator components

Table 3: Linear generator dimension

Component's Parameter	Dimension
Shaft radius	12.5 mm
Stator length	145.8 mm
Stator diameter	125.0 mm
Translator length	261.0 mm
Translator diameter	55.0 mm
Stator back iron thickness	6.5 mm
Magnet outer diameter	55.0 mm
Magnet inner diameter	47.0 mm
Magnet length	33.0 mm
Magnet spacer	5.0 mm
Air gap	1.0 mm

Two parts of simulation for linear generator have been analyzed; electromagnetic and thermal analysis. For each prototype of linear generator, various configuration and arrangement of permanent magnet on the translator and other components of linear generator have been simulated, constructed and tested. It is important to design the desired magnet dimension and other components to be used in the linear generator and to analyze the effect of temperature to the magnet. Application of $Nd_2Fe_{14}B$ magnet in linear generator has been successfully simulated using Maxwell software.

Electromagnetic analysis

In Ansoft Maxwell® 2D software, the magnetostatic and transient simulations have been performed to calculate electromagnetic parameters. These parameters are important in order to evaluate the flux distribution and flux density within the system.

Flux density determines the strength of the magnetic field of the permanent magnets. The shape and dimension of stator teeth, back iron of the stator and air gap are determined by the flux density. The induced voltage is calculated from the linkage flux in the coils. It is given by Faraday's Law,

$$e = -N\, d\psi/dt \quad (1)$$

where N is the number of turns in wire coil and $d\psi/dt$ is the derivative of magnetic flux with respect to time [16].

The main flux in the generator is generated by permanent magnet. The flux magnitude is affected by some factors, i.e., the dimension and material properties of generator magnetic components. In the design, the flux is required to be as high as possible.

Simulation results

Flux density is the main parameter that shows the general magnetic properties of the magnet. Performance of the generator can be assessed with the aid of flux distribution pattern. The flux generated by the permanent magnets will flow through coils via the air gap and the stator core. Figure 5 shows the typical flux distribution for the generator model. The typical flux density distribution of the generator is shown in Figure 6.

Both figures show the static analysis result of the machine for a certain position of the translator. The flux links the coils through the stator core that made of a permeable material. The use of permeable material is to increase the flux linkage. The dimension of the core is determined by the capability of the material to handle the flux flow. The flux density of the core should be below a material saturation value (≈2.0T) in order to avoid losses and harmonics. The value of 1.8T is usually considered as a maximum flux density. Figure 5 shows that the flux lines flows in the translator back iron behaves as a magnetic circuit. The back iron is made of the same permeable material as that of the core.

Low flux density observed in the shaft shows that the effect of shaft dimension is not significant, except in the mechanical design. A high flux density is observed at the corner. When the translator is moved, the flux density in almost parts of the stator will change. In the translator back iron, the flux density distribution will remain constant. All constraints of the component material are considered in the optimization design. Some objective functions such as power to weight ratio, power to volume ratio or power to cost ratio may be included in the optimization design to get a final design, where the flux density may be not considered as a primary factor.

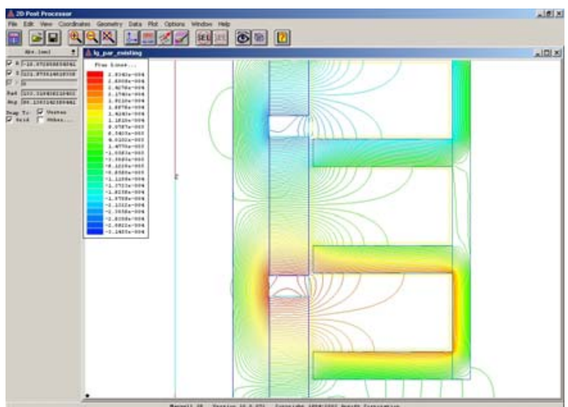

Figure 5: Flux distribution

The flux linkage curve in the coils with respect to translator displacement is shown in Figure 7. It shows the system is in a three phase machine system. The curve is plotted as a function of translator displacement. In the linear generator, the translator is not moved in a constant speed so that the induced voltage waveform will follow the speed waveform. The induced output voltage is shown in the Figure 8. The Vrms is 94 V and the generator is run at 3000rpm. The expected power that needs to be achieved for the generator is 5kW and this has been successfully simulated and fabricated.

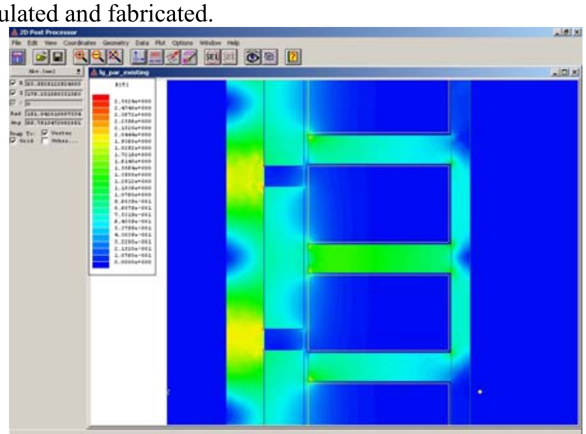

Figure 6: Flux density

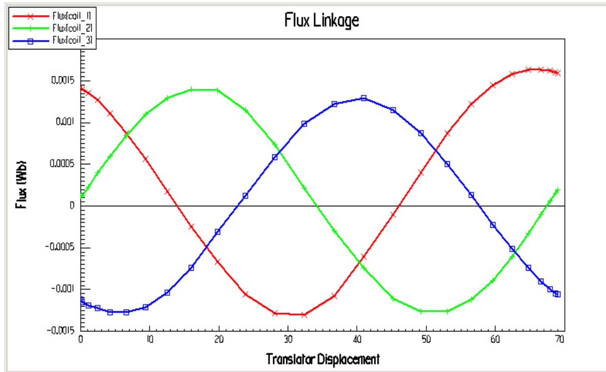

Figure 7: Flux linkage versus translator displacement

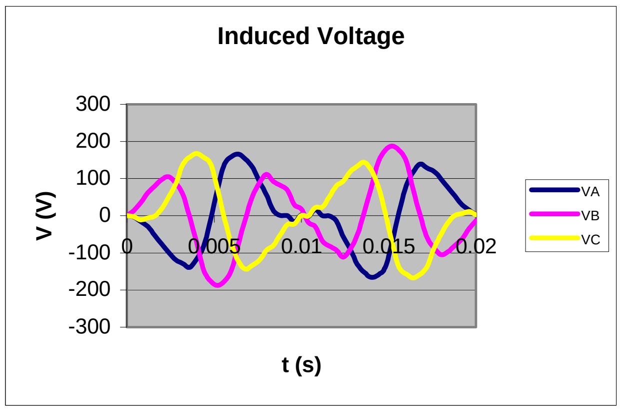

Figure 8: The induced output voltage

Thermal analysis

The effect of temperature in the linear generator system can be evaluated with the aid of thermal analysis model. The focus of our analysis is to develop a thermal model and to study the heat distribution in linear generator. Compared to other materials used, the permanent magnet temperature is one of the key items to be emphasized in generator design. A simulation is developed to ensure that the magnet can be operated at certain temperature conditions due to the limited maximum operating temperature within $Nd_2Fe_{14}B$ magnet.

A detailed study on thermal analysis of linear generator is furthered by designing a thermal model using FEM. The temperature difference at certain regions in the linear generator is then can be estimated. For thermal analysis in the linear generator, various kinds of heat sources and heat transfer mechanisms are studied. Heat sources in the linear generator include the heat from the exhaust of combustion engine, current carrying conductors and friction are investigated. In this paper, our analysis concentrates on heat sources from the internal combustion engine and the electromagnetic field part. The heat transfer mechanisms are also investigated. This analysis can be classified as one of multi-physics problems which involve conduction, convection, radiation, electromagnetic field and friction.

Governing equations

In any applications, before thermal model is designed, numerical computation should be considered and the load applied to the model should be represented by the governing equations. For linear generator, the net function of heat, which is considered to be generated, can be represented as

$$\sum f(Q) = f(Q_t + Q_e + Q_f) \qquad (2)$$

where Q_t is the heat from the combustion engine, Q_e is the heat from electromagnetic field and Q_f is the heat produced by piston and sleeve bearing through friction. In general, the heat equation is derived from the conservation of energy principle, which states that the net heat conducted out is equal to the summation of heat generated and change in energy stored within the system. Mathematically, this expression can be expressed as [17]

$$\vec{\nabla} \bullet q = Q - \frac{\partial e}{\partial t} \tag{3}$$

where q is the heat conduction, Q is the heat generated within the system and $\partial e / \partial t$ is the change in energy stored. q is described by Fourier's Law of heat conduction and is given by

$$q = -\kappa \vec{\nabla} T \tag{4}$$

Therefore, the heat transfer in a solid material is expressed by a partial difference equation as follows [17]

$$\vec{\nabla} \bullet (\kappa \vec{\nabla} T) + Q - \rho C_p \frac{\partial T}{\partial t} = 0 \tag{5}$$

where κ is the thermal conductivity, C_p is the specific heat capacity, ρ is the mass density, Q is the heat generation rate per unit volume and T is the unknown temperature distribution that is to be determined. Table 4 shows the thermal conductivities of different materials used to design the linear generator.

Table 4: Thermal conductivities of each material at room temperature

Part	**Material**	**Thermal Conductivity [W/(m-^{0}K)]**
Air gap	Air	0.0261
Magnet	Neodymium-Iron-Boron	9
Coil	Copper	401
Stator lamination, back iron (at translator)	Silicon steel	51.9
Magnet spacer, piston	Aluminium alloy	155.8
Shaft	Stainless steel	14.9
Piston pin (Gudgeon pin)	Ceramic	2.2

Simulation results

Due to the limited maximum operating temperature within the $Nd_2Fe_{14}B$ magnet, a simulation is developed using Ansoft Maxwell® 3D software to ensure that the magnet can be operated at certain temperature conditions. Figure 9 shows the 3D linear generator model which is driven by dual internal combustion engine and Figure 10 shows the temperature distribution of the permanent magnet.

From this simulation, it is observed that the maximum temperature of the permanent magnet that nearest to the combustion engine is 93.74^{0}C. It is noted by the manufacturer, that this value can be accounted as a safety margin for the permanent magnet which has maximum operating temperature of 200^{0}C. Although this temperature value is accepted, the magnetic flux density of the permanent magnet has been measured at different operating temperature in order to evaluate the performance of the generator. Figure 11 shows the percentage reduction of magnetic flux density of $Nd_2Fe_{14}B$ magnet at 80^{0}C to 200^{0}C. From the test, at the temperature condition of 93.7^{0}C, the percentage reduction of magnet performance is about 5.2%. At 200^{0}C, the magnet performance reduced to approximately 44.5%. This reduction of flux density will in turn cause the voltage drops.

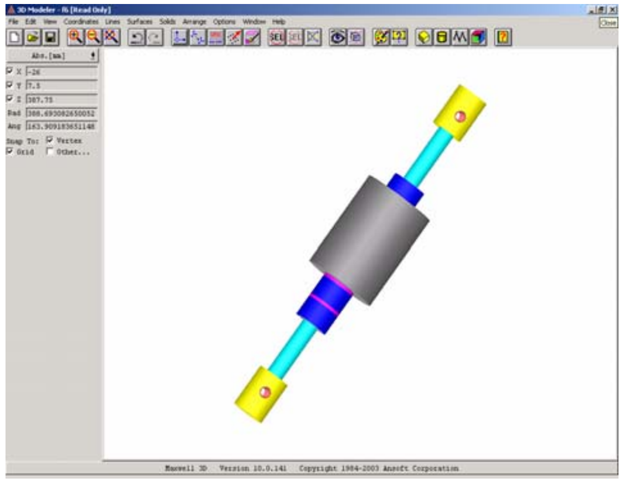

Figure 9: 3D linear generator model driven by dual internal combustion engine

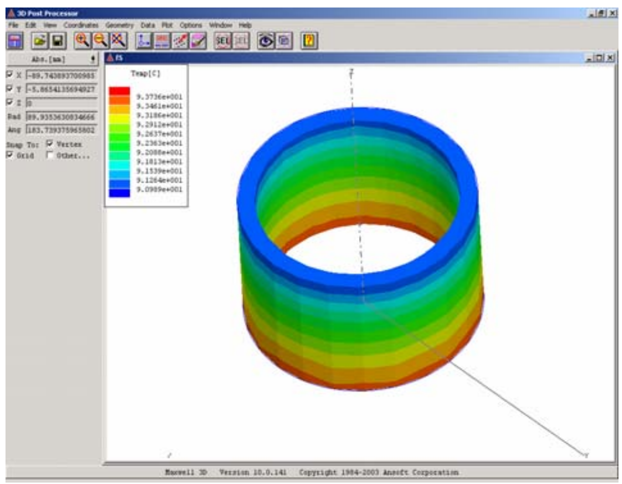

Figure 10: Permanent magnet temperature distribution (^0C)

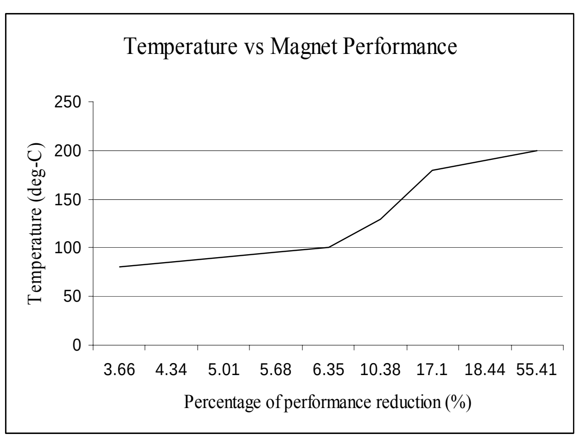

Figure 11: The percentage reduction of magnetic flux density of $Nd_2Fe_{14}B$ magnet at certain temperatures

CONCLUSION

The application of $Nd_2Fe_{14}B$ rare earth permanent magnet for linear generator design has been studied. Analysis of $Nd_2Fe_{14}B$ indicates that this material is suitable to be used in the generator design. Finite element modeling and thermal analysis aided in evaluation of its electromagnetic characteristics and the temperature tolerance.

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