International Baccalaureate

Extended Essay

Physics

Investigating how does magnetic force applied on one another by two identical magnets is affected by their temperature.

Word Count: 3335

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Introduction

I have chosen this topic to investigate because of an experiment that caught up in my mind for some time. It was about a piece of nickel metal that has been attached to the end of a metal wire and simultaneously exposed to a heat source with a permanent magnet in front of it. In the experiment the nickel is attracted by the magnet hence, moved towards the magnet. However, when it got close to the magnet it started to heat up by the heat source which caused the nickel metal to reach the Currie Temperature. At this specific temperature, the aligned domains within the nickel begun to point different directions and no longer acted as a magnet. As a consequence, the nickel turned back to its original position and cooled down. This process repeated itself over and over again. After watching this experiment I have begun to wonder the effects of different temperatures including below and above 0°C on magnets.

This investigation is based on the temperature factor that has been established to affect the magnetic force between two Neodymium magnets (NdFeB). The effect of temperature can be handled in two aspects, temperature can either strengthen or weaken the magnetic force that has been asserted on both magnets. This phenomenon occurs because of the atomic structure of the magnet. When a magnet is exposed to heat, its particles gain kinetic energy and the magnetic field is reduced because the particles within the magnet tend to move at a faster and more erratic rate. As a result, the magnetic domains get misaligned because of this interfere, thus magnetism decreases. When a magnet is subjected to low temperatures, however, its magnetic properties intensifies and its strength increases. Extreme temperatures can also cause a magnet to demagnetize, in which the magnets' properly aligned domains are divided into smaller domains that have random magnetization directions.

Different types of magnets tend to react variously with temperature changes. In case of Neodymium magnets, they are considered to have the most radical changes with temperature, whereas being the most resistant to demagnetization among other ferromagnets. This is the reason why I have chosen to work with a magnet that is sensitive to temperature changes in order to find a value in which the magnetic field strength is the highest.

Background Information

Magnetism is a natural phenomenon that occurs when a magnet exerts a magnetic force of attraction or repulsion on a charged particle. This magnetic force is caused by the motions of electric charges within a matter which creates an electric current. Every object is composed of atoms and electrons spinning around them. The magnetic property of an object is considered by the opposite or same spinning motion of its electrons. If there is an atom with most of its electrons spinning in the same direction, it is said that this element has magnetic properties.

The magnetic force between two magnetic poles on a vertical plane is expressed by this equation:

$$F_B = \frac{B^2 \times A}{2\mu_0}$$ [1]

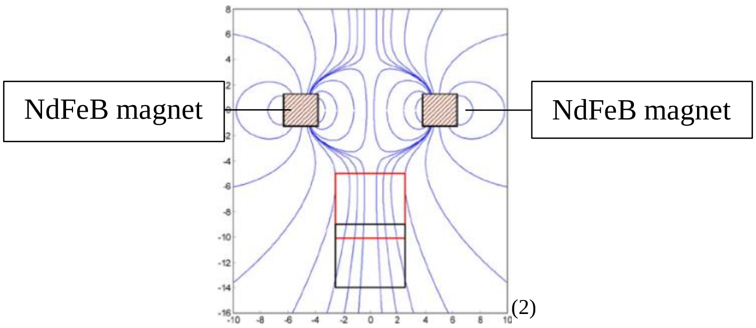
Where,
F_B: magnetic force between two magnetic poles (N)
μ_0 : magnetic permeability of vacuum ($4\pi \times 10^{-7}$ H/m).
B: flux density of magnet (T)
A: cross sectional area (m^2)

However, these magnetic properties can only arise if these objects are subjected to a magnetic field created by another magnet. Then, it is said that the object is magnetized. Apart from that,

[1] Chen, C. H., Meng, H., & Fan, M. (2018). *Magnetic Force Equation for Rare Earth Magnets and the Effect of Load Line*. 1–5. https://www.researchgate.net/publication/328824016_Magnetic_Force_Equation_for_Rare_Earth_Magnets_and_the_Effect_of_Load_Line

there are other ways to make a substance magnetized. For instance, an electric current running through a metal wire can also produce a magnetic field.

Magnetic field is a plane in which the correlation between charged electrical particles are represented. Considering magnets, the direction of the magnetic field is always from north pole of the magnet to south pole of the magnet.



(2)

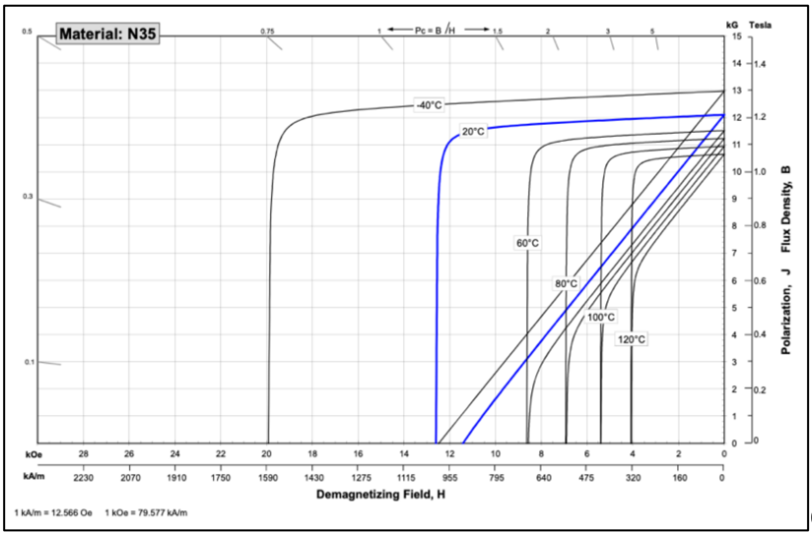
Figure 1:Magnetic fields lines of repulsive forces between two NdFeB magnet.

Neodymium magnets (also known as NdFeB, Neo, NB magnets) are ferromagnets (permanent magnets) that are composed of neodymium, iron and boron elements. They are categorized in Rare-Earth magnet family and considered to have the strongest magnetic properties among other ferromagnets.

Theoretically, NdFeB magnets can show magnetic properties between −130°C and 80°C[3]. As the temperature decreases, the magnetic field strength created by NdFeB magnets increase and it is said that these magnets tend to operate well at the temperatures below 0°C conversely, these magnets lose their magnetic properties when subjected to heat. For every degree Celsius

[2] Permanent-Magnet Helicon Discharge Array - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Field-lines-of-a-NdFeB-ring-magnet-of-3-in-ID-and-5-in-OD-with-rectangles-showing-two_fig1_252055999 [accessed 20 Jan, 2022]

the magnetic force of Neodymium magnets is scientifically proven to decrease with 0.11%[3]. Thus, if the maximum operating temperature is exceeded by a few degrees, the magnetic field strength loss could be recovered by cooling down. However, exceeding the temperature limit by far could make the magnet lose its magnetic properties permanently, causing it to demagnetize.



(4)

Graph 1:Demagnetizing Field of NdFeB (N35) magnets with respect to Polarization and Flux Density.

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The demagnetization graph regarding to the N35 quality NdFeB magnets are shown in the *Graph 1*. This graph could be used to find the operating point for a particular temperature of the NdFeB magnet. Normal curves which indicate the magnets' performance are the linear lines that have a slope of 1.05, an example of a normal curve shown in blue for 20°C.[5] The load lines

[3] *Neodymium magnets (NdFeB)*. Eclipse Magnetics. (n.d.). Retrieved December 1, 2021, from https://www.eclipsemagnetics.com/products/magnetic-materials-and-assemblies/magnet-materials/neodymium-magnet-material/.

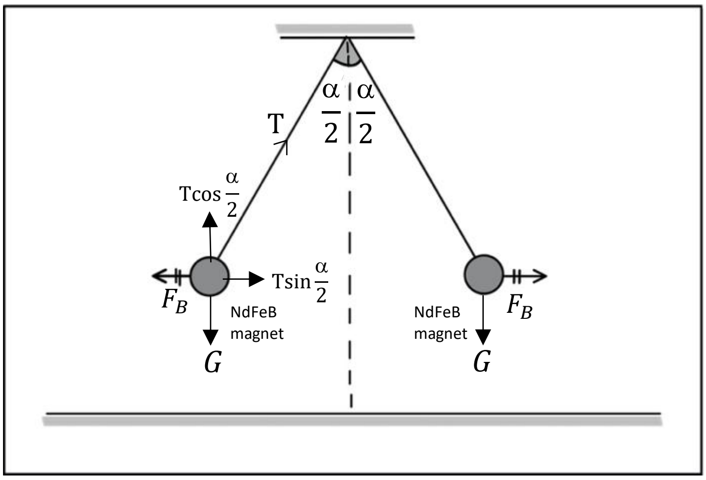
[4] *Neodymium-iron-boron magnet grades summary product list ...* Arnold Magnetics. (2019). Retrieved December 1, 2021, from https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Catalog-151021.pdf.

[5] Temperature and Neodymium Magnets. (n.d.). Retrieved February 26, 2022, from https://www.kjmagnetics.com/blog.asp?p=temperature-and-neodymium-magnets

are the linear lines that are drawn from the origin to the Permeance coefficient (P_c)(The ease which magnetic flux can pass through a material. This quantity affected by the shape and the surrounding of a magnet.). The intersection of the load line and the normal curve gives the operating point for that specific temperature.

Experimental Methodology

This investigation is based on the temperature factor effecting the magnetic field strength between two identical Neodymium magnets. This experimental setup requires two magnets fixed to face the same poles in order to repel each other on a horizontal axis and measuring the angle between these magnets when both of them are at their climax point.



Whereas;

F_B : Magnetic field force (N)

α: Angle between neodymium magnets

G: weight = m x g (N)

mass: m (kg)

gravitational acceleration: g (≅ 9.81 ms^{-2})

T: tension in the copper wires (N)

Figure 2: Experimental setup diagram shows the acting forces on the NdFeB magnets.

To calculate the Magnetic Field Force (F_B)

Tension (T) must be split up to its vector components,

$m \times g = G$

$G = T \times cos\frac{\alpha}{2}$ (Then T is replaced in the equation below.)

$F_B = T \times sin\frac{\alpha}{2}$

Variables

Independent Variable	Temperature (-20.00℃,-10.00℃, 0.00℃, 10.00℃, 20.00℃, 40.00℃, 60.00℃, 80.00℃, 100.00℃ $\pm$ 0.05℃) of NdFeB magnets.	The temperature range is selected between -20.00℃ and 100.00℃ because these are the maximum temperature limits that could be achieved using the current equipment that I have. 80℃ is purposely added to the temperature values because of the fact that theoretically this is the maximum limit that the NdFeB magnets can operate. The average difference between the temperature values is 15℃ to measure the magnetic force increase/ decrease by 1.65%.
Dependent Variable	The magnetic force exerted by the NdFeB magnets on each other.	This quantity will be measured by the angle between two magnets repelling each other.
Controlled Variables	The medium that the experiment takes place. Period of time passes to do the setup to take the measurements. The experimental materials used (NdFeB magnets). The angle of the camera. Mass of the magnets. Mass of the copper wires.	The medium that experiment takes place in is in my living room and kitchen so the magnetic permeability stays the same during the trials. The time gap (approximately 20 seconds.) between collecting data and arranging the setup is crucial and should be minimized in order to eliminate the random errors. 24 identical NdFeB magnets is used. The angle is important to measure the spread of the magnets, should be fixed to eliminate systematic error. Mass of each magnet is $3.532 \pm 0.001g$. Mass of copper wire is $0.215 \pm 0.001g$

Materials

1. Neodymium magnets (24 pieces)
2. Camera
3. Calibrated Thermometer (−50.00℃ to +300.00 ℃)(± 0.05℃)
4. Freezer
5. Boiling water in a pot (200 ±5 ml)
6. A hook (to attach the magnets to frame)
7. Copper wires (15.5 ± 0.1 cm)
8. Scissors
9. Cylindrical pen (diameter R = 0.8 ± 0.1cm)

Methodology

1. Cut one copper wire of 15.5 cm per a magnet
2. Pass the wire through the hole of the magnet
3. Determine the middle of the wire and clamp the two sides to close the magnet
4. Twist the two ends of wire with each other until it reaches 3 cm.
5. Wrap the excess wire around the pen until it reaches the twisted area.
6. Repeat the process for the other NdFeB magnet pair.
7. Have 2 NdFeB magnets in deep freezer at -20℃.
8. Attach the magnets to the hook, remember to place the magnets with same poles facing each other.
9. Start recording with the camera (in slow motion) that has been aligned with the center of the hook.
10. Film the magnets till they reach equilibrium.
11. From the video point out the places where the magnets hit their climax points.
12. Using technology, place a protractor to the screenshots of the climax points of the magnets.

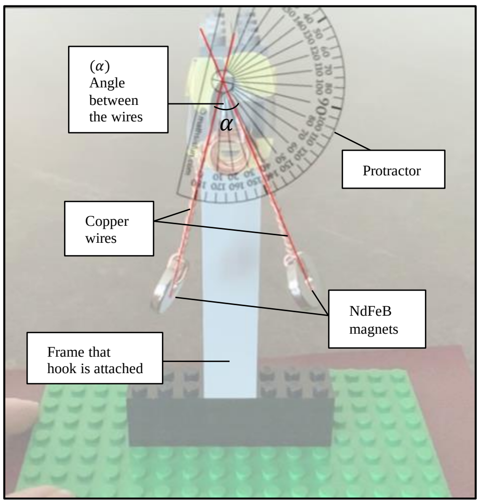


Figure 3: Measuring the angle between the copper wires using protractor.

13. Calculate the angle between the wires and record your data.
14. Repeat the whole process for 5 times.
15. Repeat the process for the magnets with -10.00, 0.00, 10.00, 20.00, 40.00, 60.00, 80.00, 100.00℃ temperature.

*Note: For the temperatures of -10.00, 0.00 and 10.00℃ keep the magnets in the freezer and wait before the magnets reach the desired heat. For 20.00℃ leave the magnets to the room temperature. For the rest of the temperature variables heat the magnets in the boiling water.

Experimentation

Raw Data Table: Effect of temperature change on the angle between copper wires.

$Temperature$ $(\pm 0.05℃)(℃)$	$Trials$	$Angle\ between\ the\ wires$ $(\pm 0.5°)(°)$	$Mass$ $(\pm 0.001g)\ (g)$ $with\ copper\ wire$
-20.00	1	87.0	3.747
	2	88.0	
	3	88.0	
	4	85.0	
	5	84.0	
-10.00	1	76.0	3.747
	2	75.0	
	3	75.0	
	4	76.0	
	5	77.0	
0.00	1	57.0	3.747
	2	56.0	
	3	55.0	
	4	56.0	
	5	56.0	
10.00	1	51.0	3.747
	2	50.0	
	3	49.0	

	4	49.0	
	5	51.0	
20.00	1	43.0	3.747
	2	45.0	
	3	43.0	
	4	43.0	
	5	47.0	
40.00	1	36.0	3.747
	2	36.0	
	3	36.0	
	4	36.0	
	5	37.0	
60.00	1	18.0	3.747
	2	19.0	
	3	20.0	
	4	18.0	
	5	18.0	
80.00	1	10.0	3.747
	2	9.0	
	3	10.0	
	4	9.0	
	5	9.0	
100.00	1	0.0*	3.747
	2	0.0	
	3	0.0	
	4	0.0	
	5	0.0	

**Note that at 100.00℃ the NdFeB magnets demagnetized thus lost their ability to repel each other*.

The uncertainty for the temperature is found by its smallest division which is 0.1 ℃ divided by 2 which equals to 0.05 ℃.

For the digital instrument, digital scale, the uncertainty is calculated by its' smallest digit 0.001 which it could read.

Finally, the uncertainty for the angle is calculated by the protractors' smallest digit which is 1° divided by 2, equal to 0.5°.

Calculations

For the data of -20℃

- Mean

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$

$$\bar{x} = \frac{87° + 88° + 88° + 85° + 84°}{5}$$

$$\bar{x} = 86.4°$$

- Range

$$Range = x_{max} - x_{min}$$

$$= 88° - 84°$$

$$= 4°$$

- Standard Deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N}}$$

$$\sigma = \sqrt{\frac{(87-86.4)^2+(88-86.4)^2+(88-86.4)^2+(85-86.4)^2+(84-86.4)^2}{5}} = 1.8165902124585$$

$$\sigma \cong 1.817°$$

- Standard Error

$$SE = \frac{\sigma}{\sqrt{N}}$$

$$= \frac{0.817°}{\sqrt{5}}$$

$$SE \cong 0.81°$$

- Absolute Uncertainty

$$\frac{(max + 0.01) - (min - 0.01)}{2} = \Delta a$$

$$\frac{(88.0 + 0.01) - (84.0 - 0.01)}{2} = \Delta a$$

$$\Delta a = 2.01 \rightarrow \Longrightarrow 86.4 \pm 2.01 \text{ ℃}$$

- Percentage Uncertainty

$$\%unc. = \frac{Absolute\ unc.}{Reading\ taken}$$

$$\%unc. = \frac{2.01}{86.4} \times 100 = 2.33\%$$

- Magnetic Force (F_B)

$$Assume\ that\ \frac{\alpha}{2} = \theta$$

$$\frac{86.4°}{2} = 43.2°$$

$$m \times g = G$$

(Unit conversion of mass: $1g = 10^{-3}kg\ \ thus,\ 3.747\ g = 3.747 \times 10^{-3}kg$)

$$3.747 \times 10^{-3} \times 9.81 = 36.758 \times 10^{-3}N$$

$$G = Tcos\theta$$

$$0.03675807\ \ = Tx\ cos43.2°$$

$$T \cong 50.425\ \ \times 10^{-3}N$$

$$F_B = Tsin\theta$$

$$F_B = 50.425 \times 10^{-3} x\ sin 43.2°$$

$$F_B = 3.451812532 \times 10^{-2}\ N$$

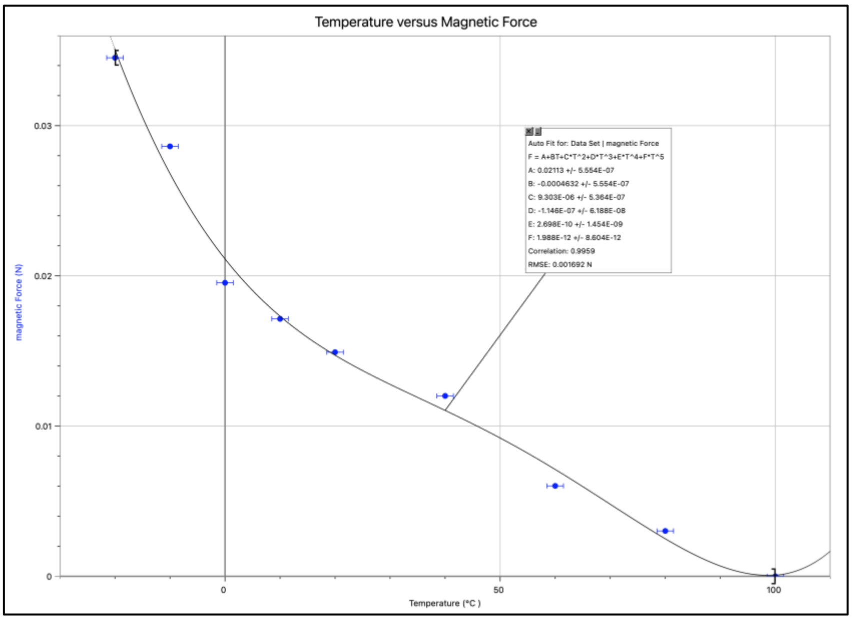
$$F_B \cong 3.452 \times 10^{-2} Newton$$

Processed Data Table

Temperature (± 0.05℃)	Mean ($angle$ °)	Range (°)	$Magnetic\ Force\ (Newton)$	Standard Deviation (°)	Standard Error (°)	Absolute Uncertainty of Temperature (℃)	Percentage Uncertainty
-20.0	86.4	4	3.452×10^{-2}	1.82	0.81	± 2.0	2.33%
-10.0	75.8	2	2.862×10^{-2}	0.75	0.33	± 1.0	1.33%
0.0	56.0	2	1.954×10^{-2}	0.63	0.28	± 1.0	1.80%
10.0	50.0	2	1.714×10^{-2}	0.89	0.40	± 1.0	2.02%
20.0	44.2	4	1.492×10^{-2}	1.60	0.72	± 2.0	4.55%
40.0	36.2	1	1.201×10^{-2}	0.40	0.18	± 0.5	1.41%
60.0	18.6	2	6.02×10^{-3}	0.80	0.36	± 1.0	5.43%
80.0	9.4	1	3.02×10^{-3}	0.49	0.22	± 0.5	5.43%
100.0	0	0	0	0	0	0	0

**Note that mean of the angle is taken to 1 decimal point whereas magnetic force, standard error and standard deviation is taken respectively to 2 decimal points.*

Data Analysis



Graph 2: Quintic line fit for Temperature versus Magnetic Force graph.

As the temperature versus magnetic force graph represents, the data shows a decrease with approximately -3 slope. It can be said with respect to the overall decrease trend, as the temperature increases the magnetic force asserted by both NdFeB magnets to each other decreases. Hence, the temperature is inversely proportional to magnetic force of repulsion.

As the seen in the *Graph 2* the correlation between magnetic force and temperature is said to be Quintic. That means magnetic force changes with respect to a fifth-degree change in temperature with a correlation of 0.9959 and can be represented as:

$$F_B = A + B \times T + C \times T^2 + D \times T^3 + E \times T^4 + F \times T^5$$

Whereas the coefficients are,

A=0.02113 B=-4.632 $\times 10^{-4}$ C= 9.303$\times 10^{-6}$ D= -1.146 $\times 10^{-7}$ E= 2.698$\times 10^{-10}$

F=1.988 $\times 10^{-12}$ N°C^{-1}

Conclusion

This Extended Essay has led me understand comprehensively the properties of magnets especially, Neodymium magnets. Also this investigation made me observe that not only temperature but various other factors affect the behaviors of magnets. Such as the magnetic force could be related with the magnets geometric shape, its quality (in this case N35), the magnetic permeability of the medium and so on.

General findings from this investigation is that, the magnetic field force is inversely proportional to the magnets' temperature. As the independent variable, the temperature increases gradually from $-20.00℃$ to $100.00℃$ the magnetic force decreases proportionally to the 5^{th} power of temperature.

Moreover, at the maximum operating temperature is $80℃$, it has been observed that the magnets still repel each other with a 3.02×10^{-3}N magnetic force. Similarly, a complete demagnetization of the NdFeB magnets has been observed when the magnets heated up to $100.00℃$ which matches with the theoretical values.

There is not a linear but a general decreasing trend in the temperature versus magnetic field force graph drawn. As the raw data graph suggests, the temperature and the magnetic force variables have a quintic relationship between them. Hence as the temperature decreases, the magnetic properties of NdFeB magnets increase, which results in an increase in magnetic repulsion forces between two identical magnets.

Discussion

Throughout this investigation there have been various factors that might have caused some errors. These errors could be counted as systematic and random errors.

For systematic errors, that might have caused by the inaccuracy from the measurements, can be counted as: the data taken from the thermometer, the angle of the camera and the heat loss during average of 20 seconds time gap before the experiment. These errors can be reduced by calibrating the thermometer, conducting the experiment in a medium which is specifically arranged to keep a constant temperature or minimizing the time gap between collecting the magnets to place them on the hook. And if the frame on which the experiment was done could be fixed to a specified point which is also aligned with the angle of the camera.

As it comes to random errors, it was difficult to adjust the magnets facing the same poles. To avoid them turning in the middle of the experiment, I used copper wires to hold them in place. Copper wires solved that problem because, they were light in weight (theoretically 0.215 g) and make the magnets stay fixed by compressing them from their edges. Pointing out the climax points was done by hand so the selected points could have minor differences with the real climax points, by increasing the number of trials this factor could be eliminated or decreased.

If there was a specific magnetic field around the medium which couldn't be controlled, this could also affect the collected data.

The strength of this investigation is that the upper limit of demagnetization for NdFeB magnets had been observed. This also suggests that the obtained data proves the previous findings from the scientific journals' which makes the data reliable and accurate . As the last operating temperature point of NdFeB has been determined as 80℃ beforehand the experimentation.

However the weakness of this investigation is that the time gap between preparing the magnets to the specific temperature and conducting the experiment had taken about 20 seconds approximately. This situation should have resulted in a heat loss, thus a temperature loss and should have affected the accuracy of the data without affecting its precision, because the time gap is roughly same for all the data collected.

The limitation of this investigation was the temperature range. The temperature values below -20.00 °C couldn't be observed due to the lack of equipment. If the temperature range of the NdFeB magnets could be lowered to -130.00°C by dipping the magnets in liquid nitrogen, which theoretically is the minimum temperature that these magnets operate, the maximum magnetic force could be observed and obtained. This temperature could allow the experimenter to observe the maximum magnetic repulsive force.

Additionally, as an improvement for this investigation the maximum temperature range can be increased. If the temperature of the magnets could reach up to 310.00°C, which is the Curie temperature for N35 quality Neodymium magnets, temporary paramagnetic behaviors of the ferromagnet NdFeB magnets could also be observed.

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