Physics IA

Research Question: What is the relationship between the magnetic field strength of a permanent magnet and its temperature?

11 Pages

Introduction

When I was a little child, my father bought me some magnets to play with. I would attach the magnets to various metallic items in my home. In winter I once submerged my hand inside freezing water, then managed to hold the magnet. The magnet was bitterly cold because of its metal covering. I then came up with the question: is the magnetic field strength affected by the temperature?

During a physics class, the teacher taught me that when the temperature of an electromagnet increases, its magnetic field strength decreases. Unfortunately, she didn't mention the temperature effect on permanent magnets. My curiosity was aroused to see if temperature will have a similar influence on permanent magnets. Therefore, I decided to research into the relationship of temperature and magnetic field strength of a permanent magnet.

Variables

There are two essential variables in this experiment.

Table 1. Variables in the experiment

Name	Meaning	Type of variable	Unit
t	Temperature of the permanent magnet	Independent	Celsius (°C)
B	Magnetic field strength of the permanent magnet	Dependent	gauss (Gs)

Equipment for measurement

- A 1L beaker
- A kettle
- A thermometer with thermocouple
- A gauss meter
- A strong permanent magnet
- Clamp and stand

Method

1. Bring the gauss meter to the hallway where almost no magnets are nearby and return the reading of the gauss meter to zero.

2. Roughly estimate the magnetic field strength. Using the gauss meter, the magnetic field strength almost reaches zero as the probing pin goes farther than 5cm from the pole. Therefore, to ensure that the magnitude of the data is big enough, I decided to keep the distance between probing pin and magnetic pole to be within 5cm.
3. Set up the clamp and stand, and fix the gauss meter at one clamp. Entwine the wire of the thermometer around the magnet to form a spiral shape. This process reduces the time spent on winding and fixing the wire on the magnet.
4. Put the magnet in the kettle with water and heat it up.
5. After a while, take the magnet out of the hot water and entwine the wire around the magnet, then attach the magnet to a clamp. Put the probing pin on one magnetic pole.
6. Record the temperature and magnetic field strength in two columns as the magnet cools down.

Figure 1. The magnetic field strength at 5cm far is almost zero

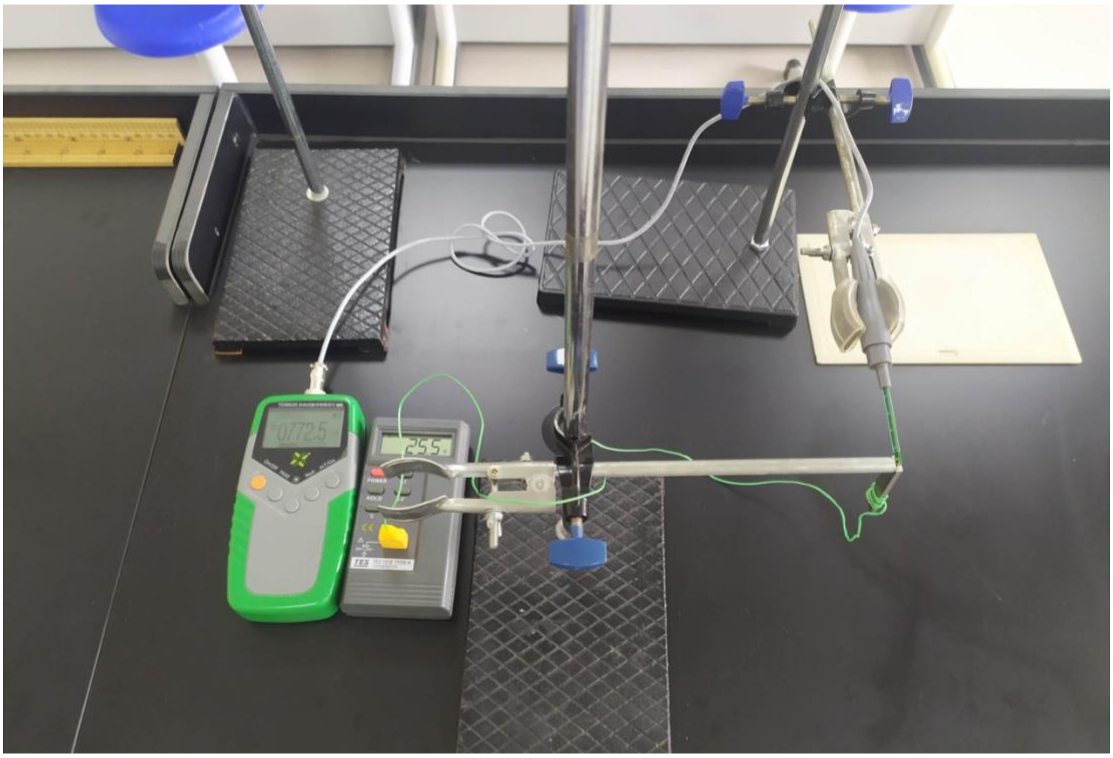

Figure 2. Setting up the apparatuses – front view

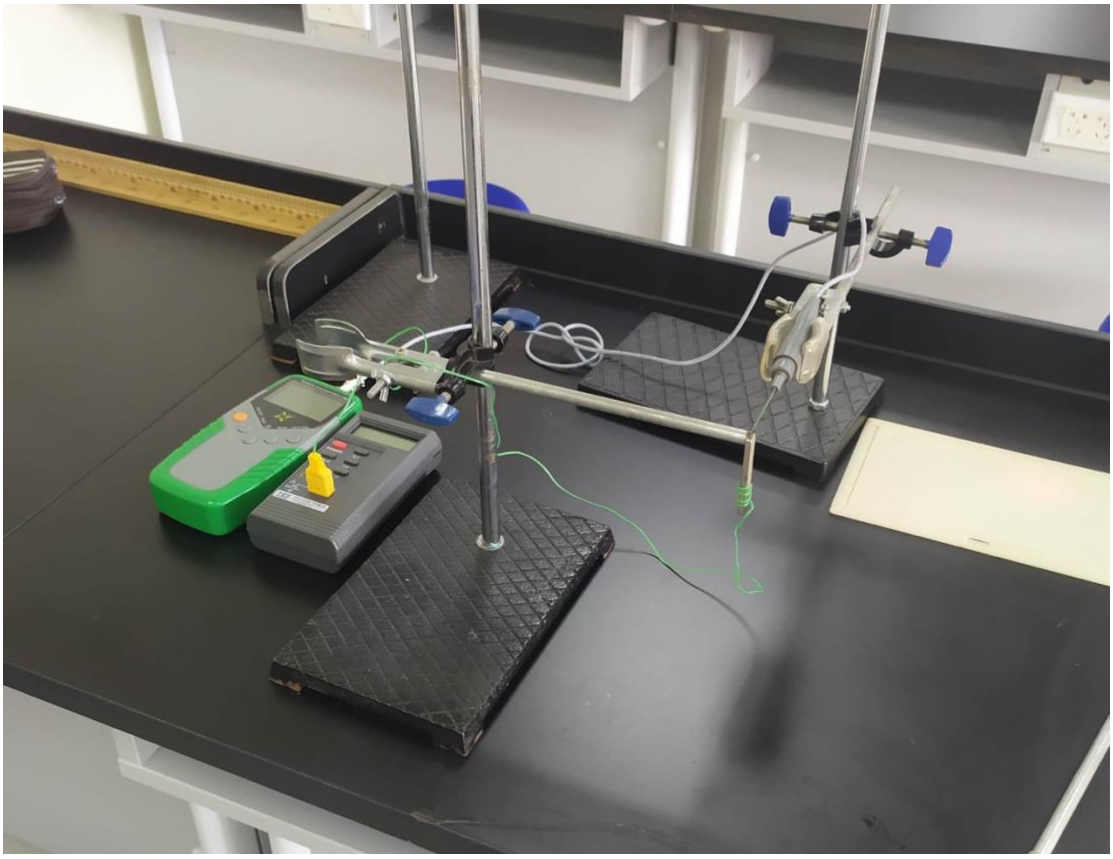

Figure 3. Setting up the apparatuses – side view

On Figure 3, the leftmost green apparatus is the gauss meter and the grey apparatus near it is the digital thermometer. The magnet is hung on the clamp.

Data and Analysis

The data I obtained from this experiment is shown below.

Table 2. Raw data

Temperature (°C)	**Magnetic Field Strength (Gs)**
47.3	751.1
46.6	752.6
46.2	753.6
45.1	755.3
44.6	751.3
44.2	751.8
43.4	753
41.1	753.7
40.6	754.8
39.5	755.1
38.9	755.3
38.6	755.5
38.4	756
38.1	756.2
37.5	756.3
36.5	756.7
35.8	757
35.4	756.5
34.8	757
34.3	757.1
33.9	757.4
33.5	757.2
33.2	757.4
32.8	757.6
32.4	757.9
32	758.1
31.6	758
31.4	758.3
31	758.6
30.6	758.8
30.2	759.1

29.7	759.3
29.3	759.6
28.8	759.9
28.3	760.1
27.9	760.3
27.5	760.5
27	760.7
26.6	760.6
26.2	760.8
25.8	762

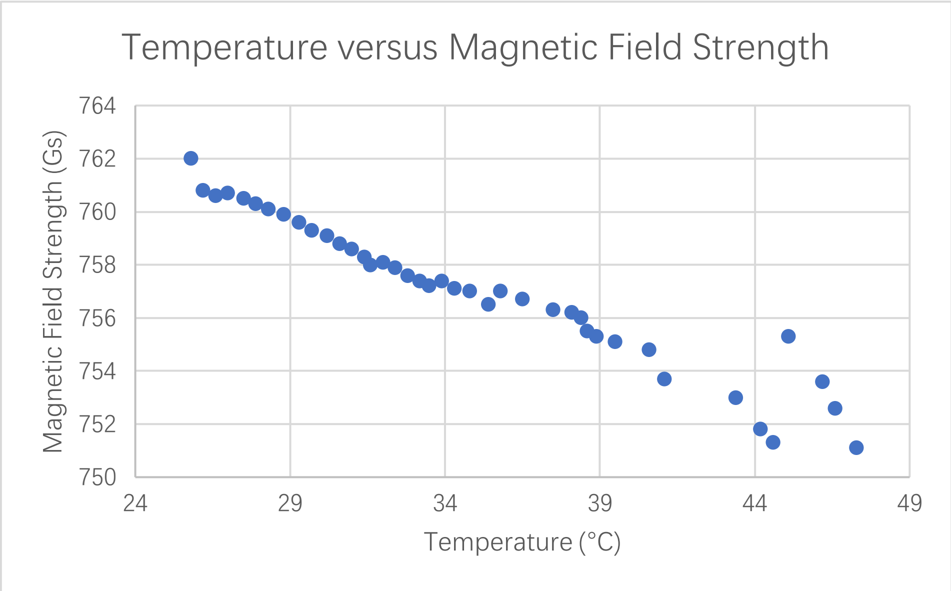

Figure 4. Graph for raw data in Table 2

The general pattern of the points is a line. However, note that the four rightmost points do not fit in that line; instead, they form a new line. I considered these points as outliers, so I would exclude them from the dataset. Their presence is probably explained by the unstable state of the magnet as it was just attached to the clamp.

In addition, I planned to record the uncertainty in data, and the error bars may be a mess if the points are so condensed. Therefore, I decided to clear out some points while keeping the general pattern. For the adjusted dataset, every two adjacent points would roughly differ by 1℃ in terms of temperature.

The adjusted data set is shown below.

Table 3. Adjusted raw data

Temperature (°C)	Magnetic Field Strength (Gs)
44.6	751.3
44.2	751.8
43.4	753
41.1	753.7
40.6	754.8
39.5	755.1
38.4	756
37.5	756.3
36.5	756.7
35.8	757
34.8	757
33.9	757.4
32.8	757.6
32	758.1
31.4	758.3
30.6	758.8
29.7	759.3
28.8	759.9
27.9	760.3
27	760.7
26.6	760.6
25.8	762

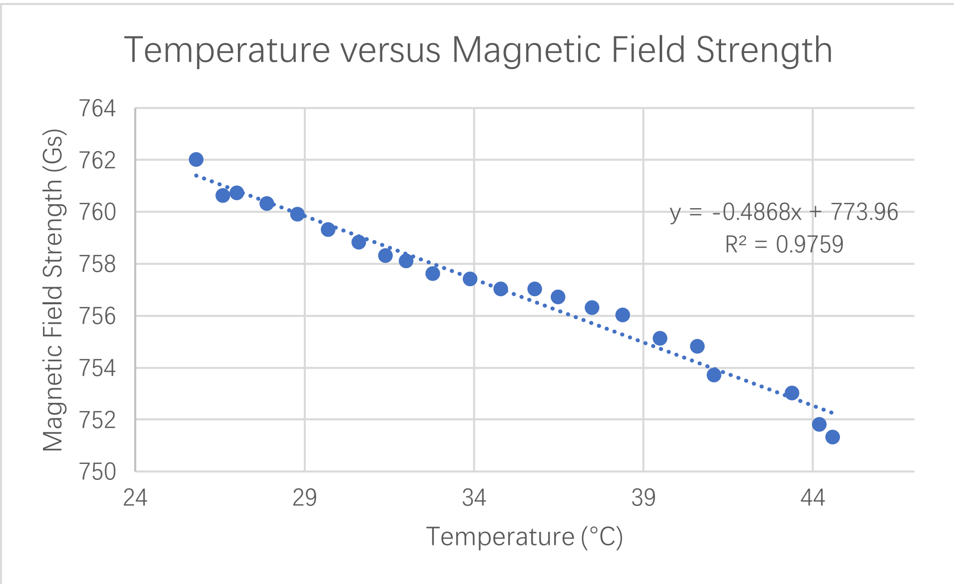

Figure 5. Graph for adjusted raw data in Table 3

A linear regression model is generated by Excel. I also switched the regression model to nonlinear.

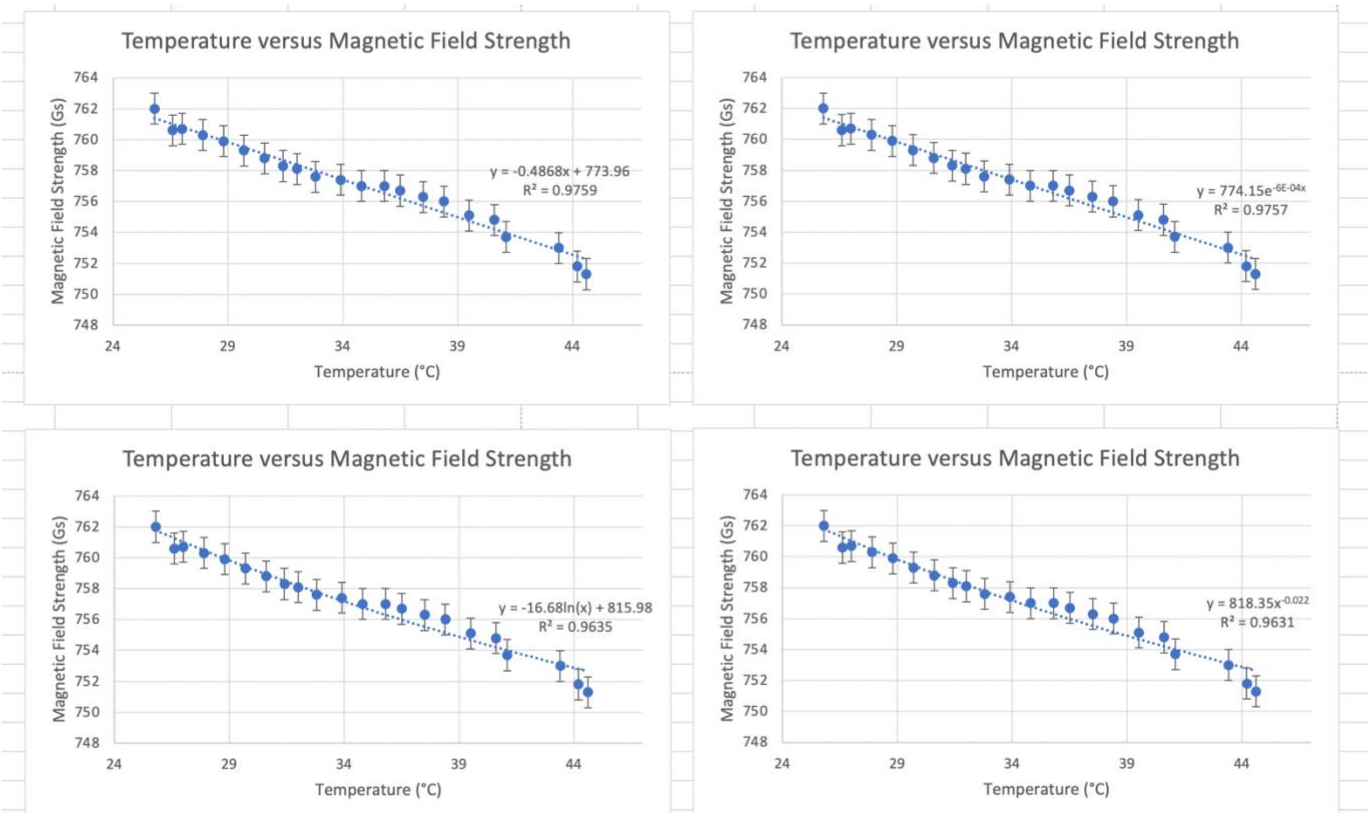

Figure 6. Four linear regression models

In Figure 6, the regression models are respectively: linear, exponential, logarithmic and power. The logarithmic and power regression line does not pass the error bar of the last point, so these two models are abandoned. Consider linear and exponential models. Excel produced a R^2 value, also known as coefficient of determination in statistics, for each model. "The better the linear regression fits the data, the closer the value of R^2 is to 1" (Coefficient of determination - Wikipedia, 2021).

Table 4. R^2 value for each model

Option	Equation	R^2 value
Linear	$y = -0.4868x + 773.96$	0.9759
Exponential	$y = 774.15e^{-0.0006x}$	0.9757

The R^2 value for the linear trendline is closest to 1, so it fits with the data set most accurately. Moreover, even though the R^2 value for the exponential trendline is very close to that of the linear one, the exponent on e is $-0.0006x$, too small to be considered as "exponential" as the trendline seems almost linear. Hence, I claim that the temperature affects magnetic field strength in a linear relationship.

There is uncertainty in measuring both the temperature and magnetic field strength. Because the apparatus has limited accuracy in measurement, the value is inaccurate to the smallest division. For the thermometer, the uncertainty is ± 0.1℃, while for the gauss meter, the uncertainty is ± 0.1Gs. The uncertainty in temperature is negligible since it is too small; on the other hand, when I observed the reading from the gauss meter, the reading fluctuates constantly, so I decide to increase the uncertainty on magnetic field strength to ± 1Gs. The vertical error bar of width 1Gs is added on the points. Two straight lines are plotted to represent the greatest and least possible gradient of a best-fit line.

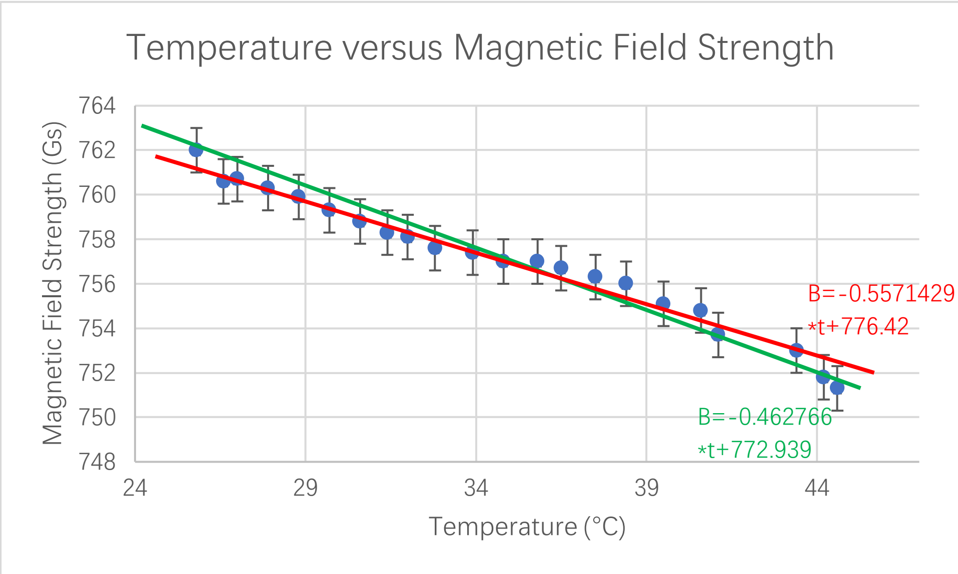

Figure 6. Graph of adjusted new data with error bars

In Figure 6, The red line represents the curve with greatest gradient, equation: $B = -0.5571429t + 776.42$. The green line represents the curve with least gradient, equation: $B = -0.462766t + 772.939$. Note that they both pass all error bars. Then the best-fit line equation is:

$$B = \frac{-0.5571429 - 0.462766}{2}t + \frac{776.42 + 772.939}{2}$$
$$= -0.50995445t + 774.6795$$

The uncertainty in slope is $\pm(0.50995445 - 0.462766) = \pm 0.04718845$. The uncertainty in B-intercept is $\pm(774.6795 - 772.939) = \pm 1.7405$. Therefore, when the uncertainty is taken into account, the best-fit line equation is:

$$B = (-0.50995445 \pm 0.04718845)t + (774.6795 \pm 1.7405)$$

For the linear trendline generated by Excel, $y = -0.4868x + 773.96$, both the slope and intercept are within the uncertainty. Therefore, this trendline also conforms with the linear model.

Hence, the temperature affects the magnetic field strength of a permanent magnet in a negative, linear way.

Evaluation

There are several limitations for my experiment.

First, the temperature range in my experiment is only $25 \sim 48℃$, so the linear relationship may not be applicable at higher temperatures. I had attempted alternative methods, either to submerge the magnet inside a cup of water and heat the water up, or to place the magnet inside an infrared remote heater, but both attempts cost more time to complete than my final experiment design.

Additionally, the thermometer I used detects the temperature using a small node, and I can only place the node close to the magnet rather than right on the magnet. Therefore, the temperature I measured is slightly less than the actual temperature of the magnet, causing an underestimate of the temperature and an overestimate of the gradient of the best-fit line.

I can further improve my experiment by:
1. Wrap insulators around the magnet to reduce heat loss and produce more data
2. Use a computer to automatically record data in a chart to reduce uncertainty and produce more data
3. Submerge the magnet in water and heat up the water to heat the magnet to higher temperatures
4. Use an infrared remote heater to heat the magnet to higher temperatures

Despite all those limitations, there are certain advantages as well:
1. The use of accurate digital apparatuses ensures high accuracy of data
2. A R^2 value close to 1 proves the linear relationship
3. My consideration of uncertainty appropriately calculates a best-fit line

Conclusion

This paper briefly introduces an experiment that measures the relationship between temperature and the magnetic field strength of a permanent magnet. I design an experiment and record a magnet's temperature and magnetic field strength while it cools down.

After that, I analyze the data. I first identified and removed outliers, then decreased the data density for the convenience of adding error bars. After that, I switched different regression models and selected linear and exponential model, then compared their R^2

values to prove that the linear model fits most accurately. I also took uncertainties to account and produce a best-fit line: $B = (-0.50995445 \pm 0.04718845)t + (774.6795 \pm 1.7405)$. Thus, temperature negatively affects the magnetic field strength of a permanent magnet in a linear way.

I also analyzed the advantages and drawbacks of my experiment. More work is required to get a deeper investigation on the influence of temperature.

Reference

1. En.wikipedia.org. 2021. *Coefficient of determination - Wikipedia*. [online] Available at: <https://en.wikipedia.org/wiki/Coefficient_of_determination> [Accessed 2 October 2021].