

A MODEL EXPERIMENT FOR TEACHING THE HYSTERESIS LOOP

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Abstract. Learning the formation of the hysteresis loop can help students to understand the ferromagnetic properties of materials. Also, studying the hysteresis loop gives a brief idea about the relationship between the magnetic flux density \mathbf{B} , magnetic field strength \mathbf{H} and magnetization \mathbf{M} . In the present study, a model experiment is presented which was prepared for learning the fundamentals of the hysteresis loop. The results of this easy and instructive experiment are substantially compatible with theoretical knowledge.

Key words: model experiment, hysteresis loop.

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1. INTRODUCTION

As mentioned by Chabay and Sherwood [1], electromagnetic interactions have an important role in determining the structure of the natural world. Hence, understanding these interactions may help students understand electricity and magnetism topics. The topic of the magnetic field by itself is very abstract, but our experience with this field comes from observing its effect on materials [1]. Therefore, understanding the magnetic properties of materials is important in terms of learning the phenomena of magnetism. It is stated in the studies conducted by Guisasola *et al.* [2], Tanel and Erol [3] and Guisasola *et al.* [4] that students have some difficulties and misconceptions about explaining magnetic properties of materials and matter-magnetic field interactions. It is thought that studying the hysteresis loop may help to resolve the problems students face. However, learning the properties of the hysteresis loop only theoretically by using textbooks may not provide this since there are some common misconceptions, misinterpretations and distinct notions concerning the presentation of the hysteresis loop in undergraduate textbooks [5, 6]. In addition, there are similar problems about the concepts of

magnetic field strength \mathbf{H} and magnetic flux density (magnetic induction) \mathbf{B} [7–10] which are very crucial in understanding the hysteresis loop. For these reasons, students experience serious confusion about the properties of the hysteresis loop.

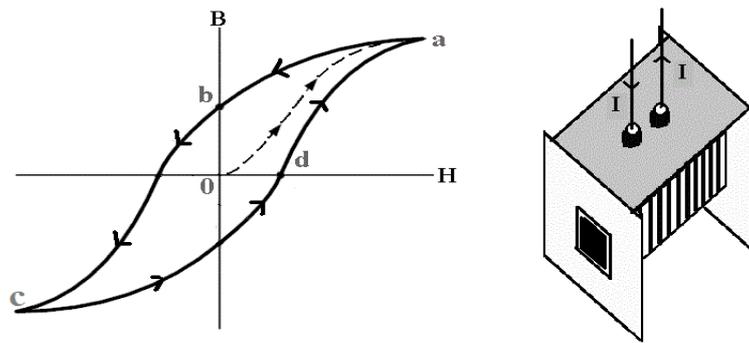


Fig. 1 – A typical hysteresis loop of a ferromagnetic core inside the current-carrying coil.

The hysteresis loop of a ferromagnetic core is shown graphically in Fig. 1. This graph indicates that the relationship between \mathbf{B} and \mathbf{H} is non-linear. Drawing every path of this graph (0-a, a-b, b-c, c-d, d-a) can be carried out by changing the value and direction of the current in the coil as explained in the related web information [11, 12].

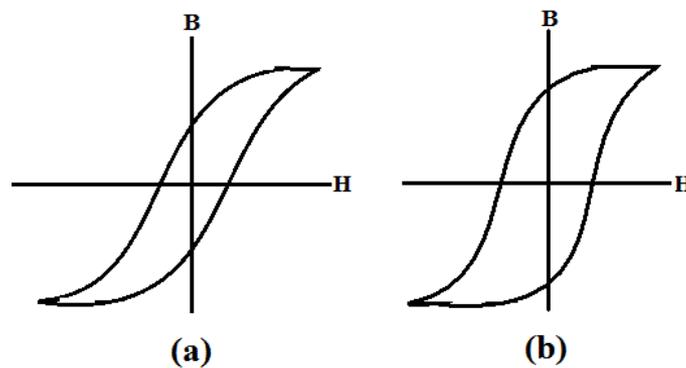


Fig. 2 – The hysteresis loop of a ferromagnetic core which has higher permeability (a) and lower permeability (b).

On the other hand, as stated in electronics-tutorials [11], NDT resource center [12] and Boyacıoğlu [13], the area within the hysteresis loop is dependent upon the permeability of the ferromagnetic core. As shown in Fig. 2a, a narrower loop indicates that the ferromagnetic core inside the coil has higher permeability. A wider hysteresis loop occurs in the core which has lower permeability as in Fig. 2b. The carbon content of a ferromagnetic material is an important predictor of its

permeability. The addition of carbon to the material causes a decrease in permeability so it will have low permeability.

Considering the difficulties highlighted in the literature, performing an experiment in this topic related to basic information concerning the formation and structure of the hysteresis loop as mentioned above can be more useful for students.

On the other hand, it has been seen that the experiments which have been carried out in related literature for this purpose generally include a method that is based on directly viewing the hysteresis loop on the oscilloscope [14–16]. These experiments can be successful in teaching the differences of shape between hysteresis loops of different materials. Also, these will be more powerful for exact measurements of hysteresis properties of materials in material sciences. Direct viewing, however, provided by the use of an AC current may prevent the understanding of the paths followed for the occurrence of the hysteresis loop. In one study [17], a DC current was used for teaching these paths. It is therefore thought that this study is more suitable for instructional purposes. The application of the experiment considered in this study is simple and instructive. The inductance equation used to calculate the magnetic permeability in this study, however, may not mean much to students who are new in magnetic field issues. The concept of self-inductance and related information are taught towards the end of the electricity and magnetism course. Thus, this instructive experiment can be performed by experienced students.

In the present study, the aim was to perform a model experiment that is suitable for students, and which is basic and instructive. There are two main reasons for the experiment to be called a model:

- 1) The measurements are related to the effect of the magnetic flux density of the core material and are not exact values of flux density inside the material.
- 2) The curve produced is not the actual hysteresis curve of the material but rather a sample curve produced to give an idea about the formation of hysteresis loop and the magnetic properties of the materials.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. PRINCIPLE OF EXPERIMENT

Two identical solenoids are placed as shown in Fig. 3. The solenoid on the right side is called “R”. The solenoid on the left side is called “L”. The currents of I_L and I_R that are applied to the solenoids create magnetic fields in the same direction. Also, there is a compass at the point where the central axes of the solenoids intersect.

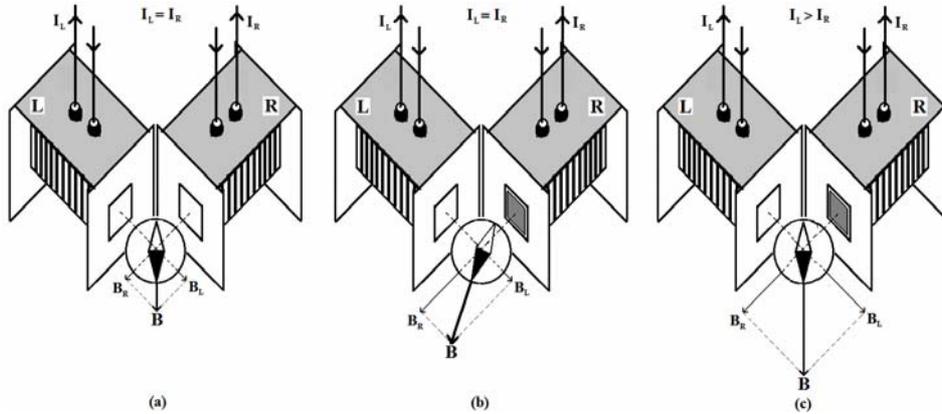


Fig. 3 – Position of compass needle in the situation of: a) $B_R = B_L$; b) $B_R > B_L$ due to magnetization of ferromagnetic core; c) $B_R = B_L$ due to increased current I_L .

In Fig. 3a, the magnitude of the magnetic flux density (\mathbf{B}_{in}) inside the coils with the air core can be identified with the equations:

$$B_{inR} = \mu_0 H_R = \mu_0 n I_R \quad (1)$$

$$B_{inL} = \mu_0 H_L = \mu_0 n I_L. \quad (2)$$

In reality, these values will be reduced at the point where the compass is placed due to the distances from the centre of coils. So, there is an air gap between the compass and coils. The main purpose of this experiment was to compare effects rather than make a calculation. At this indicated point, the magnitudes of \mathbf{B}_R and \mathbf{B}_L are directly related to I_R and I_L , respectively. Therefore, magnitude differences between \mathbf{B}_{inR} , \mathbf{B}_{inL} and \mathbf{B}_R , \mathbf{B}_L can be neglected for the purpose of this experiment. The same approach can be used for examinations of both Fig. 3b and Fig. 3c. Because the currents of I_R and I_L are equal, the magnitudes of \mathbf{B}_R and \mathbf{B}_L will be equal. Hence, the direction of \mathbf{B} , which is the combination vector of \mathbf{B}_R and \mathbf{B}_L will be as shown in Fig. 3a and the N pole of the compass needle will show this direction.

Inserting a ferromagnetic core into the centre of R, as shown in Fig. 3b, increases the magnitude of \mathbf{B}_{inR} . The magnetization of the ferromagnetic material causes this increase. In this case, the magnitude of \mathbf{B}_{inR} is given by the equation:

$$B_{inR} = \mu_0 (M + H) = \mu H_R = \mu n I_R. \quad (3)$$

Although the I_R current is unchanged, this effect also increases the magnitude of \mathbf{B}_R . Therefore, the direction of \mathbf{B} changes as a result of this. This situation can be observed by looking at the change in the position of the compass needle as shown in Fig. 3b.

The magnitude of \mathbf{B}_{inL} can be increased by increasing the current I_L . When this current was increased until the point at which the compass needle assumes the same position as in Fig. 3a, both of the magnitudes of \mathbf{B}_R and \mathbf{B}_L will be equal as shown in Fig. 3c. In this case, the magnitudes of \mathbf{B}_{inR} and \mathbf{B}_{inL} will also be equal. This relationship of the magnitudes of these can be defined as by using (2) and (3):

$$\mu_0 n I_L = \mu n I_R. \quad (4)$$

It can be seen that $\mu_0 n I_L$ corresponds to the magnitude of magnetic flux density inside the material according to (4). Thus, by using the equations (3) and (4), it can be accepted that I_L is the determinative of \mathbf{B}_R and I_R is the determinative of \mathbf{H}_R . Therefore, the relationship between \mathbf{B} and \mathbf{H} can be examined with the relationship between I_L and I_R and the I_L - I_R curve can be thought of as the \mathbf{B} - \mathbf{H} curve.

Any change in the direction and in the value of I_R changes the magnetizing field \mathbf{H}_R . The effect of this field can be compensated by changing the direction and the value of I_L while observing the orientation of the compass needle as mentioned below.

2.2. APPARATUSES AND THEIR PROPERTIES

Two identical solenoids which have 600 turns of insulated wire, a resistance value of 2.5Ω and an inductance value of 9 mH were used for this experiment. These coils can carry a maximum current of 2A. The current of the R and L coils were provided by using a dual tracking DC power supply (TOPWARD 630D). This source can provide the desired current values directly and these values can be seen from the front panel of the source. The effects of the magnetic flux densities of the coils were observed by using a compass divided into 360 degrees. Two different ferromagnetic cores were used in the measurements to show the effect of the permeability of the materials on the hysteresis curve. One of these was a standard iron transformer core and the other a steel core (SAE 1040) which contains more carbon.

2.3. CALIBRATION OF EXPERIMENTAL SETUP

Before starting the measurement of the I_R and I_L currents in the experiment, the following calibration operations will be useful.

Firstly, the compass is placed at the point where the central axes of the solenoids intersect. The position of the compass needle is aligned with the horizontal component of the Earth's magnetic field as shown in Fig. 4.



Fig. 4 – The compass needle is aligned with the horizontal component of the Earth's magnetic field.



Fig. 5 – Because of the interaction between the ferromagnetic core and compass needle, the needle turns towards R.



Fig. 6 – The table is rotated clockwise to return the initial position of the needle.

The needle of the compass is a small magnet. Because of the interaction between the core and this small magnet, when a demagnetized ferromagnetic core is inserted into the R, the needle turns towards R as shown in Fig. 5. The magnetic field of earth can be used for compensating this effect. The experiment apparatus is for this reason placed on a rotating table. To return the initial position of the needle as in Fig. 4, the table is rotated clockwise as shown in Fig. 6.

The magnetic fields of the connecting cables could be another undesired influence in this experiment. The orientation of the compass needle can be affected by the magnetic field of the current-carrying wires. To minimize this effect, cables are intertwined as shown in Fig. 7. This method may prevent the occurrence of a bigger net magnetic field around the cables.

Finally, the magnetic field of coils can cause movement of the compass and ferromagnetic core. For this reason, they should be fixed.

2.4. TAKING MEASUREMENTS

The experimental setup was created after performing all calibrations as shown in Fig. 7. It can be seen from Fig. 7 that the compass needle shows zero degree, which corresponds to the diagonal through the point of intersection of the axes at the beginning of the experiment.

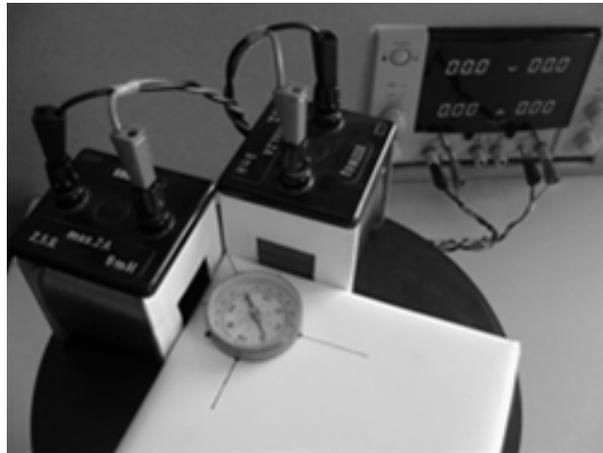


Fig. 7 – The main experimental setup.

As an example for the measurements, if current I_R is increased to 0.15 A, the compass needle will be oriented as shown in Fig. 8.

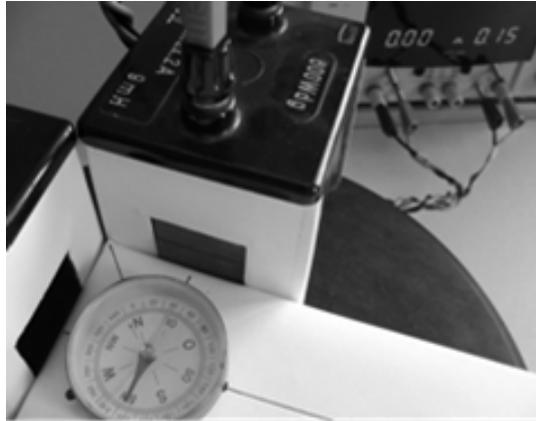


Fig. 8 – The position of the compass needle for $I_R = 0.15$ A and $I_L = 0$ A.

As shown in Fig. 9, current I_L is then increased up until the compass needle comes to the same position as in Fig. 7.



Fig. 9 – The position of the compass needle for $I_R = 0.15$ A and $I_L = 0.57$ A.

These measurements are repeated by changing the value of current I_R between 0 A and 0.45 A in intervals of 0.05 A. Both of the I_R and I_L currents flowing through the coils are also reversed to draw the paths of 0 to -0.45 A and -0.45 A to 0 A. For the purpose of reaching better magnetization inside the materials, only current I_R is increased to the value of 4–5 A for a very short time at the end of the paths of 0 to 0.45 A and 0 to -0.45 A. The graph of the I_L - I_R is plotted for the values of the I_L and I_R .

3. RESULTS

To create a model of the hysteresis loop, measurements were made for I_R and I_L currents. I_L currents were obtained by changing the value and direction of the I_R current as mentioned above. Dots of the graphs in Fig. 10 and Fig. 11 are plotted by using the values of these currents.

As a result of increasing the I_R current from 0 A to 0.45 A, the dots shown by the diamond symbols (◆) in Fig. 10 and Fig. 11 were obtained. The paths formed by these diamond symbols in Fig. 10 and Fig. 11 correspond to path "0-a" in Fig. 1. This path starts from the origin and ends at the point "a". The dots indicated with disc symbols (●) in Fig. 10 and Fig. 11 were obtained by reducing the I_R current from 0.45 A to 0 A. The paths formed by these disc symbols correspond to the "a-b" curve drawn from the point "a" to the point "b" in Fig. 1.

The dots which are shown with the triangles (▲) in Fig. 10 and Fig. 11 were obtained by increasing the I_R current from 0 A to 0.45 A after reversing the direction of this current. These changes are expressed as a range of "from 0 to -0.45A" in the graphs. The paths taken through these triangles in each graph correspond to the "b-c" path shown in Fig. 1. When the reversed current I_R is decreased from 0.45 A to 0 A (expressed as a range of "from -0.45 to 0 A" in the graphs), the dots indicated with squares (■) in Fig. 10 and Fig. 11 were obtained. The "c-d" path of the hysteresis curve in Fig. 1 is modeled by the paths that are plotted using these squares. The direction of the I_R current is reversed again after reaching the point "d". In this case, the I_R current is increased from 0 A to 0.45 A again and the points which are shown with thick lines (≡) in Fig. 10 and Fig. 11 are obtained. The paths taken through these points in each graph correspond to the "d-a" path shown in Fig. 1.

It is seen that the graphs drawn after the completion of the process described above are good in terms of modeling the path which was traced in drawing the real hysteresis curve. The experiments that have been carried out in related literature generally include a method that is based on directly viewing the hysteresis loop on the oscilloscope [14–16]. It is thought that direct viewing, however, provided by the use of an AC current may prevent understanding the paths followed for the occurrence of the hysteresis loop. Also, the "0-a" path cannot be observed on the oscilloscope screen. Therefore, it is thought that this model experiment helps students to understand the formation process of the hysteresis loop.

The relationship between I_L and I_R looks linear in these graphs and if μ is calculated by using these graphs, value of it can be found very small compared to the exact value of the μ for a ferromagnetic material. There are two main reasons of these problems. The first one is the air gap between the core and the compass. The second one is the magnetic effect of the left coil on the core. These may be the weak points of this model experiment. However, considering that this model

experiment was performed for educational purposes, these weaknesses may not be considered important.

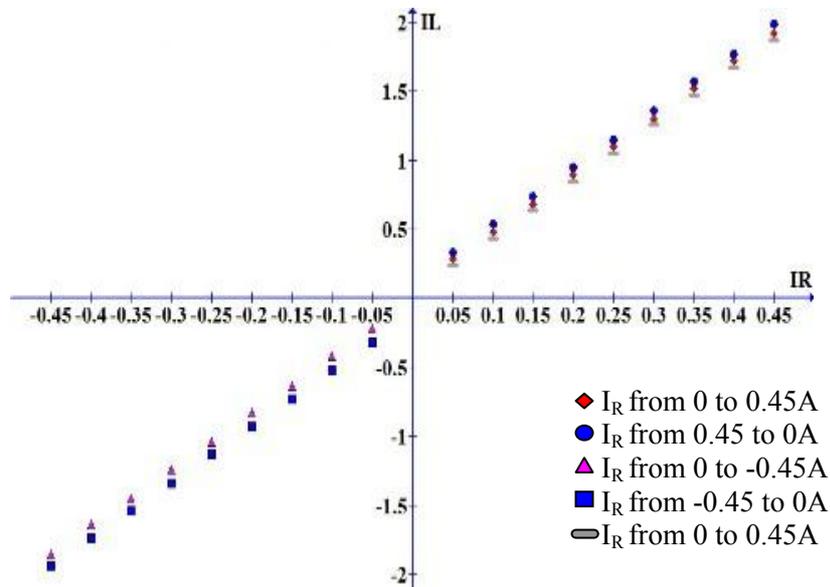


Fig. 10 – The graph of the I_L-I_R for the iron core.

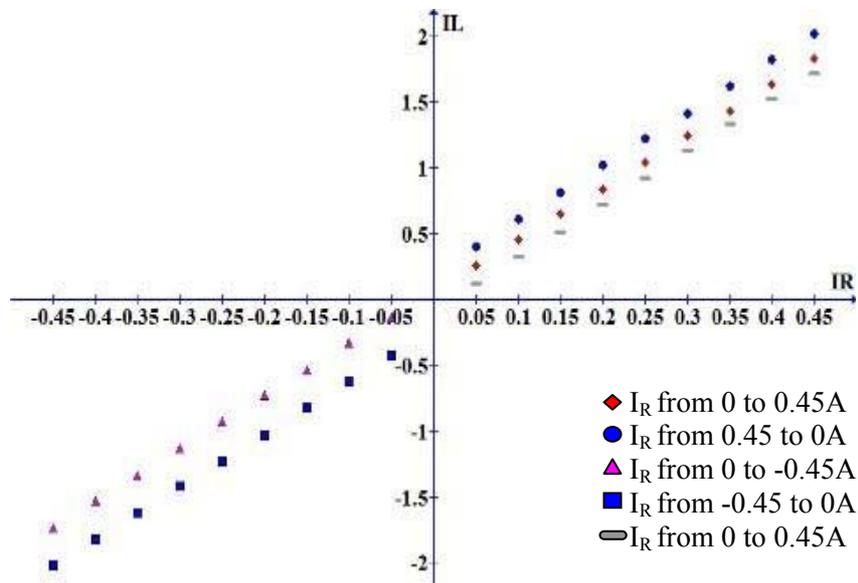


Fig. 11 – The graph of the I_L-I_R for the steel (SAE 1040) core.

The graph of the data collected by using the iron core is seen in Fig. 10. Figure 11 includes the graph of the data collected by using the steel core. It can be seen clearly that the graph of the iron core is narrower than the graph of the steel core. As explained previously, the reason for this is the carbon content of these ferromagnetic materials. Carbon is added to steel in the production stage. The addition of carbon to the material causes a decrease in permeability so it will have low permeability. A wider hysteresis loop occurs in the core which has lower permeability. In this case, it can be said that the graphs in Fig. 10 and Fig. 11 successfully modelled the real hysteresis curves in Fig. 2a and Fig. 2b respectively. This feature of the model experiment can make a positive contribution to teaching the magnetic properties of ferromagnetic materials.

4. CONCLUSIONS

In the present study, we developed an experiment that successfully models the hysteresis curve. It can be said that the graphs, that were developed in our experiment are in accordance with the formation theory of the real hysteresis curve. There is a very clear similarity between the formation paths of the real hysteresis curve and the formation paths of these graphs. On the other hand, thickness differences between the hysteresis curves of the two cores depending upon their carbon content can also be seen in these model graphs.

The laboratory experiments play an important role in facilitating the understanding of abstract physics concepts. Besides this, the experiments increase students' interest in studying Physics [18]. However, the use of experiments in physics lessons is limited by the cost of laboratory instruments and the difficulties in the use of complex experimental setups. Therefore, the development of experiments that are performed using cheap and simple materials is extremely important in the field of physics education.

No calculations have been made in this model experiment. Students can reach these conclusions only through observation and comparison. The creation of the experimental setup is quite simple and straightforward. Therefore, this model experiment would be very useful for introductory level students. Students can easily gain fundamental information about the hysteresis curve and ferromagnetic properties of materials. This experiment can also help students learn the meaning of the equation of $\mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H})$.

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