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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Magnetization Curves and Numerical Analysis of Energy Losses in Fe_3O_4 and $CoFe_2O_4$ Composite Materials Doped with Magnetic Nanoparticles

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Abstract

In this study, the magnetic properties and energy losses of polyester doped with Fe_3O_4 and $CoFe_2O_4$ magnetic nanoparticles were investigated at room temperature using the finite element analysis method. The magnetic hysteresis loops were calculated using numerical integration methods such as the Trapezoidal rule, Simpson's 1/3 rule, Simpson's 3/8 rule, and Newton-Cotes. The effects of different doping ratios on magnetization and energy losses were analyzed. As a result of the comparison of integration methods, it was revealed that the Newton-Cotes method provides more reliable findings compared to other methods. It was also reported that the Simpson's 1/3 rule method has lower error rates compared to the Trapezoidal method in iron-containing composites. Besides, the obtained results show that the Newton-Cotes method is more effective in calculating the integral of complex magnetic hysteresis curves. It was emphasized that the results of these analyses can be used in improvements and developments for the design and optimization of magnetic materials.

Keywords: Finite element analysis, hysteresis loop, energy losses, numerical integration.

I. INTRODUCTION

Magnetic materials and magnetic material-containing composites have a wide range of applications in magnetic resonance imaging technology, motor and actuator production, and the nanoelectronics industry. For these applications, the inclusion of additives in magnetic nanoparticles has enabled the production of magnetic materials with different and remarkable properties. These two materials, magnetite (Fe_3O_4) and cobalt ferrite ($CoFe_2O_4$) are extensively utilized in biomedical, electronic, and energy storage fields because of their magnetic characteristics [1-3]. The analysis of magnetic properties and energy losses in nanoparticle-doped materials is particularly important for their use in applications such as electric motors, transformers, and magnetic storage devices [4, 5].

Recent studies on magnetic materials and nanocomposites have primarily focused on the synthesis of experimental magnetic nanoparticles and the characterization of their physical properties. Additionally, numerous studies have been published on the doping of carbon nanotubes into polyester-based composites and the determination of their electrical properties [5, 15]. It is quite difficult to determine the chemical structure of the product formed during the process of adding magnetic nanoparticles to the material and after the production stage. Therefore, the results may vary depending on the usage rates of the material components, the production method, and the measurement conditions. [1,6]. New methods need to be developed to determine the combination of particle structures and their contribution to the magnetic properties of the material. The function and performance of magnetic materials are determined by magnetization and hysteresis loops, and the area under these curves determines energy loss. Therefore, the total area of the hysteresis loop is directly related to the energy loss of the material and is critical for efficiency [6-12]. The hysteresis loop shows how a material responds to an applied magnetic field (H) and how the magnetic flux density (B) changes within the material, depending on the doping ratio of magnetic nanoparticles [1,6,13]. These studies are generally aimed at improving the efficiency of magnetic materials and minimizing energy losses. Additionally, the effects of thermal factors such as temperature on magnetic properties and energy losses have been investigated [8-12]. However, there are very few studies on the numerical calculation of magnetization and energy losses in Fe_3O_4 and $CoFe_2O_4$ nanoparticle-doped polyester-based composites. This study is conducted for this purpose.

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In this study, a model function is proposed for the formation of magnetization and hysteresis curves in a magnetic field for composites doped with Fe_3O_4 and $CoFe_2O_4$ magnetic nanoparticles at different ratios. Additionally, the areas between the hysteresis curves are calculated using numerical Trapezoidal rule, Simpson's 1/3 rule, Simpson's 3/8 rule, and Newton-Cotes methods [11] to determine the magnetization behavior and energy losses of the samples, and the error values for each method are determined. The results are compared with similar studies in the literature.

II. METHOD

2.1. Model of Nanoparticle-Doped Materials

When magnetic nanoparticles are added to a polyester (PU) composite, magnetization occurs. Magnetization (M) is the density of magnetic dipole moments within a material. Mathematically, magnetization is defined as:

$$M=\sum \frac{m_i}{V} \quad (1)$$

where m_i is the magnetic moment of each magnetic dipole in the material, and V is the volume of the material.

In this study, a model is proposed for plotting the magnetization curve. Magnetization (M) is defined in relation to the magnetic field strength (H), and the magnetic hysteresis loop of magnetic materials shows the relationship between magnetic flux density (B) and magnetic field strength (H). Therefore, the following mathematical function is defined to model the magnetization curve: The fundamental magnetization relationship is:

$$B = \mu_0(H + M) \quad (2)$$

where B is the magnetic flux density (Tesla, T), H is the magnetic field strength (Ampere/meter, A/m), M is the magnetization (Ampere/meter, A/m), and μ_0 is the magnetic permeability of free space ($\mu_0=4\pi\times10^{-7}$ H/m).

In this study, the change in magnetization with respect to magnetic field strength (H) is modeled using the hyperbolic tangent (tanh) function. This model realistically represents the saturation behavior of magnetic materials. As a simple model without coercivity and hysteresis and reversibility, magnetization can be described by the following relation. The magnetization (M) can be expressed as follows:

$$M\,(H) = M_s \tanh\left(\frac{H}{H_0}\right) \quad (3)$$

where M_s is the saturation magnetization, i.e., the maximum magnetization value of the nanoparticle-doped material, and H_o is the magnetic field scaling factor or the magnetic field strength required for the material to reach magnetic saturation. The magnetic flux density (B) is modeled using the relationship between magnetic field strength (H) and magnetization (M) as follows:

$$B = \mu_0\left(H + M_s \tanh\left(\frac{H}{H_0}\right)\right) \quad (4)$$

This model is used to represent the magnetic hysteresis loop of magnetic materials. As the magnetic field strength (H) increases, the magnetization (M) reaches saturation. At small H values ($H \ll H_o$), $\tanh(H/H_o)$, i.e., the magnetization value, increases linearly. At large H values (i.e., $H \gg H_o$), $\tanh(H/H_o)$ approaches $\tanh(H/H_o)\rightarrow 1$ and reaches saturation ($M(H)\rightarrow M_s$).

The area of the hysteresis loop corresponds to the energy lost in the magnetic material over one cycle. This energy loss is expressed in Joule/cm³ or J/m³ and is calculated using the following integral. The energy loss is:

$$W = \oint B dH \quad (5)$$

where B is the magnetic flux and H is the magnetic field value. This integral represents the closed area of the hysteresis loop and can be calculated using numerical integration methods such as Trapezoidal, Simpson, or Newton-Cotes. In this study, the following functions are used to model the magnetic properties of Fe_3O_4 and $CoFe_2O_4$ nanoparticle-doped materials. The variation of magnetization depending on the doping concentration k.C (k: constant) can be described by the relation given below.

$$M_s(H) = M_{s0}(1 + kC)\ \tanh\left(\frac{H}{H_0}\right) \quad (6)$$

where C represents the nanoparticle doping ratio, H is the magnetic field strength (A/m) and H_o is the characteristic field parameter describing the saturation behaviour. The magnetic flux density for magnetic material can be written as:

$$B_{CoFe_3O_4,\ CoFe_3O_4} = \mu_0(1 + C)\tanh\left(\frac{H}{H_0}\right) \quad (7)$$

This formulation enables the calculation of magnetic flux density within the simulation framework by simultaneously accounting for the applied magnetic field and the contribution of nanoparticle doping to the magnetization process. In this study, H_0 = 50 A/m for

Fe_3O_4 magnetic nanoparticles and H_0= 40 A/m for $CoFe_2O_4$ magnetic nanoparticles. Fe_3O_4 is a soft magnetic material with a relatively low coercive field (H_c), and it can reach saturation at lower magnetic field strengths. The value of 50 A/m is chosen to realistically model the saturation behavior of Fe_3O_4. $CoFe_2O_4$, on the other hand, is a hard-magnetic material with a higher coercive field H_c and requires a higher magnetic field to reach saturation. The value of 40 T is chosen to realistically model the saturation behavior of $CoFe_2O_4$ [10].

2.2. Numerical Methods

Both magnetization and energy losses in magnetic materials are proportional to their dimensions. In this study, the sample dimensions are taken as 0.2 cm × 0.4 cm × 0.4 cm. The following four numerical integration methods are used to calculate the area of the hysteresis loop. One of these is the numerical Trapezoidal integration method. In this method, the saturation magnetic field values +H and -H are determined and divided into n segments. The magnetic flux density values -B and +B corresponding to each segment are connected, and the areas of the resulting triangles are calculated. This process starts from -H and continues to +H. Thus, the area under the hysteresis curve, and consequently the energy losses, are calculated as:

$$W = \sum_{i=1}^{n} \frac{(B_{i+1}+B_i)}{2}(H_{i+1}-H_i) \quad \textbf{(8)}$$

where B is the magnetic flux density and H is the magnetic field strength. In general, the composite Trapezoidal rule results in an error relative to the real value, and this error is defined as the difference between the integral value and the numerical result [11,16]. The error is calculated as:

$$e = -\frac{(b-a)^3}{12n^2} f^{(2)}(\xi) \quad \textbf{(9)}$$

where ξ is a number between b and a. $\xi \to 0$, it is possible to produce a value closer to the true value. Thus, when the points a and b are connected, the area of the resulting trapezoid is calculated, and if the integral is concave upwards, the error is negative, and the Trapezoidal rule estimates the true value more meaningfully.

To determine energy loss, the 1/3 rule, a numerical integration method based on second-degree interpolation, is used, and the composite Simpson's 1/3 rule is evaluated. For N = 2, Simpson's 1/3 rule is defined as follows. In the Newton Cotes integration model, the degree was taken as N= 3. In the hysteresis curve, the saturation magnetic flux density values -B and +B are defined for points a and b, and the calculation is performed for n segments with h=(b-a)/n. Thus, Simpson's 1/3 rule is:

$$W \approx \frac{h}{3}(B_o + 4\sum B_{tek} + 2\sum B_{çift} + B_n) \quad \textbf{(10)}$$

The error for n=2 is calculated as:

$$e = -\frac{1}{90} h^5 f^{(4)}(\xi) \quad \textbf{(11)}$$

The error term is proportional to the fourth derivative, which shows that Simpson's rule provides exact results for any polynomial.

Simpson's 3/8 Rule: Additionally, the Simpson 3/8 Method is used to calculate energy losses. For n=3, the area between the hysteresis curves is calculated using the 3/8 rule as follows:

$$W = \frac{3h}{3}(B_o(H_0) + 3B(H_1) + 3B(H_2) + B(H_3)) \quad \textbf{(12)}$$

This method uses third-degree interpolation and provides high accuracy.

Newton-Cotes Integration: The third method is the Newton-Cotes numerical integration method, which is calculated using the following formula [11,16]:

$$W \approx \sum w_i\, B(H_i) \quad \textbf{(13)}$$

where w_i is the Newton-Cotes coefficient, and $B(H_i)$ is the magnetic flux density corresponding to the magnetic field value. The difference between the approximate value calculated using Newton-Cotes integration and the true integral value is expressed as the error term [11,16]:

$$e = -\frac{(b-a)^3}{(n+3)!} f^{(n+2)}(\xi) \quad \textbf{(14)}$$

where b-a is the integration interval, n is the degree of the polynomial used, $f^{(n+2)}(\xi)$ is the (n+2) th derivative of the function, and ξ is a point between $a \le \epsilon \le b$.

III. RESULTS and DISCUSSION

The magnetic flux density B corresponding to the magnetic field H for Fe_3O_4 and $CoFe_2O_4$ magnetic nanoparticles doped at 1.0–3.0 wt% concentrations exhibits hysteresis behavior. To describe this physical behavior, appropriate code was written using the Python programming language, and graphs were generated using Matplotlib. Thus, Figure 1 shows the behavior of the hysteresis curves for two different magnetic nanoparticle doping ratios. Each sample reaches saturation in the range of -25 A/m≤H≤+50 A/m and -25 A/m≤H≤+50 A/m.

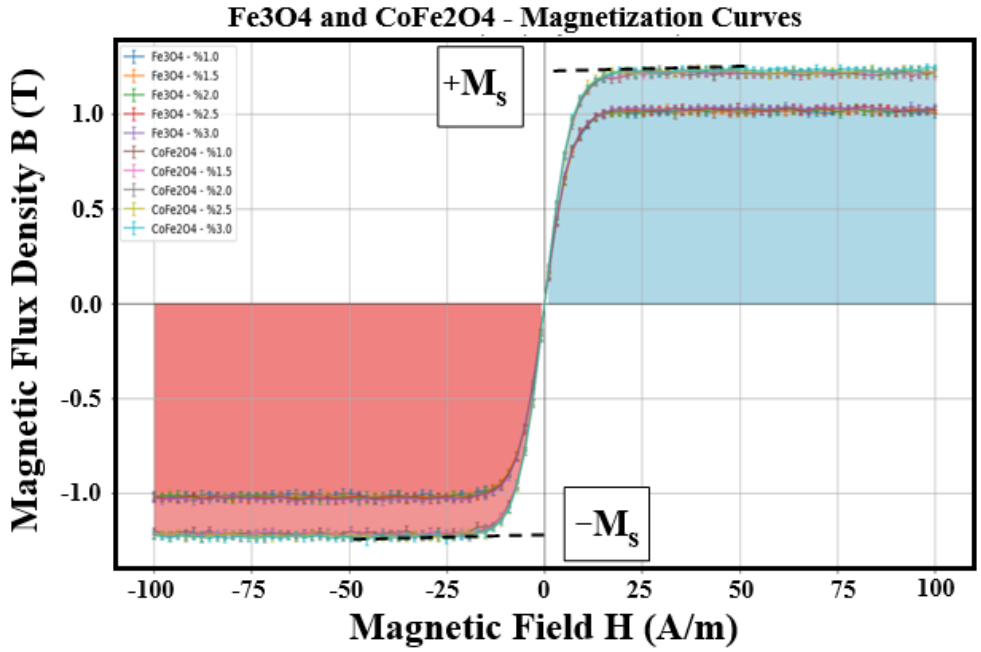

Figure 1. Hysteresis curves for Fe_3O_4 and $CoFe_2O_4$. The area between the magnetic field H values and the magnetic flux density B curves is shown in red and blue.

Additionally, as seen in Figure 1, as the nanoparticle doping ratio increases, the curves widen, and the area between the magnetic field and magnetic flux density increases. Using the hysteresis curve data shown in Figure 1, energy losses were calculated for samples doped with Fe_3O_4 and $CoFe_2O_4$ magnetic nanoparticles at different ratios using the Trapezoidal, Simpson 1/3, Simpson 3/8, and Newton-Cotes methods. The error values for each method were determined and are shown in Table 1. As seen in Table 1, as the nanoparticle doping ratio increases, the magnetization values increase. This is an expected result. Energy loss varies depending on the doping ratio of magnetic nanoparticles. Fe_3O_4 and $CoFe_2O_4$ nanoparticle doping ratios show an increase in energy loss, and similar values are obtained for the numerical methods used. Errors occur in the application of numerical methods, and the Newton-Cotes method has the smallest error value. Therefore, it can be recommended as the most suitable and usable method for calculating energy loss values.

Table 1. Energy loss values and error results calculated using numerical methods for samples doped with Fe_3O_4 and $CoFe_2O_4$ magnetic nanoparticles at different ratios.

Material			Energy Loss (J/m³)				Computational Error (%)		
	Doping (wt%)	Magneti z. (A/m)	Trapezoid al	Simpson (1/3)	Simpson (3/8)	Newton-Cotes	Simpson 1/3	Simpson 3/8	Newton -Cotes
Fe_3O_4	1.00	1.010	123.400	123.450	123.455	123.457	0.0054	0.0009	0.0005
	1.50	1.015	234.500	234.560	234.565	234.566	0.0034	0.0011	0.0004
	2.00	1.020	345.600	345.670	345.675	345.676	0.0026	0.0010	0.0006
	2.50	1.025	456.700	456.780	456.785	456.786	0.0020	0.0008	0.0004
	3.00	1.030	567.800	567.880	567.885	567.886	0.0018	0.0007	0.0003
$CoFe_2O_4$	1.00	1.210	678.900	678.890	678.895	678.896	0.0017	0.0009	0.0006
	1.50	1.215	789.000	789.000	789.005	789.007	0.0016	0.0008	0.0005
	2.00	1.220	890.100	890.110	890.115	890.117	0.0015	0.0007	0.0005
	2.50	1.225	901.200	901.220	901.225	901.226	0.0016	0.0008	0.0006
	3.00	1.230	1012.000	1012.330	1012.335	1012.330	0.0015	0.0007	0.0005

The variation of magnetization with the doped nanoparticle ratio is shown in Figure 2. The alteration in magnetization varies with the applied magnetic field. In particular, Fe_3O_4, being a soft magnetic material, produces lower magnetization values compared to $CoFe_2O_4$.

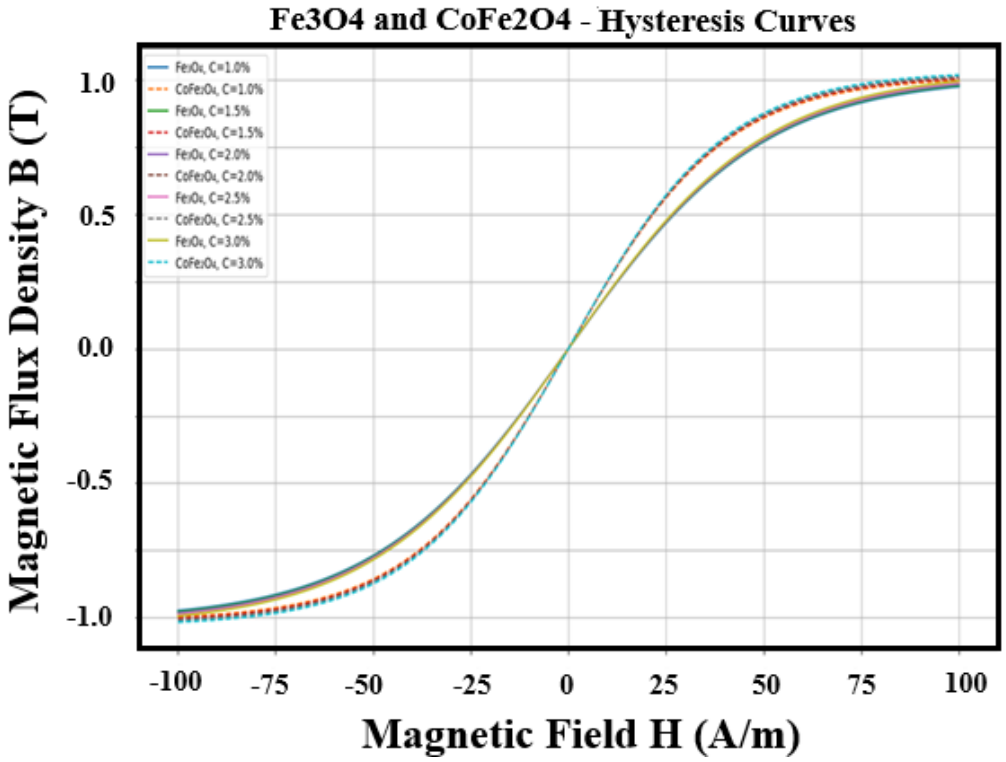

Figure 2. The variation in magnetization with magnetic field H for Fe_3O_4 and $CoFe_2O_4$.

The variation in energy loss values with nanoparticle doping ratio for the numerical methods used is shown in Figure 3(a) and the bar graphs are shown in Figure 3(b). It is shown that the energy loss values for both samples are approximately the same for the Trapezoidal, Simpson (1/3), and Simpson (3/8) methods. However, the energy loss value calculated using the Newton-Cotes method is quite different, and the error value is very small. The trapezoidal, Simpson 1/3, and Simpson 3/8 methods yield similar results for both materials, but the Newton-Cotes integration method significantly reduces the computational error and provides superiority in this regard. This increases the accuracy of the Newton-Cotes method's numerical integration, enabling more reliable results in energy loss analyses. Therefore, comparing the different methods strengthens the methodological robustness of the study.

The new method proposed in this study is a pioneering work, as similar approaches for such materials are lacking in the literature. The results obtained are indirectly evaluated using general performance metrics to demonstrate the potential benefits of the method for such materials. Furthermore, the model used is intended to provide recommendations for improving the quality of such materials before they are manufactured. It is undoubtedly recommended that this method be tested on different datasets or scenarios, as well as conducting detailed experiments, for a more comprehensive comparison.

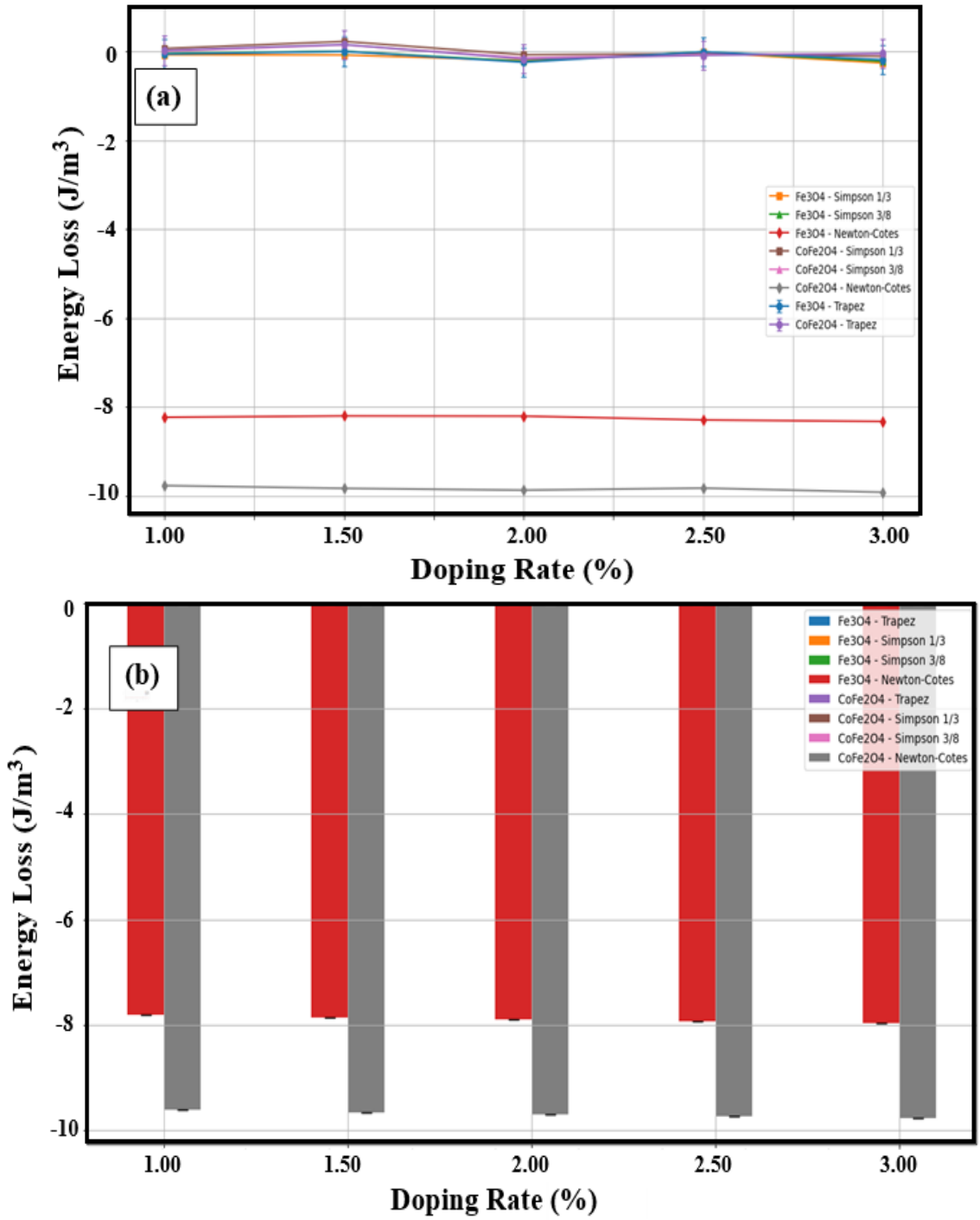

Figure 3. (a) Comparison of numerical methods used to calculate energy loss for Fe_3O_4 and $CoFe_2O_4$. (b) The presentation of the energy loss-nano doping ratio alteration with bar graphs.

A comparison of the findings in this study with the values in the literature is presented in Table 2. The calculated energy loss value for the Fe_3O_4/PU composite with a 2% by weight additive in this study is approximately 345 J/m³, while the energy loss value reported in the literature for the Fe_3O_4/epoxy composite with a 2% by weight additive in the study by Bircakova et al. is 280 J/m³ [6]. This difference is thought to be due to the resin difference (epoxy instead of polyurethane), production conditions, particle distribution characteristics, and experimental measurement conditions.

Table 2. Estimated energy loss and magnetization values for Fe_3O_4/PU ve Fe_3O_4/Epoxy samples

Materials	Doping ratio (wt%)	M_s (A/m)	Energy Loss (J/m³)	References
Fe_3O_4/PU	2.00	81.20	345	(This study)
Fe_3O_4/Epoxy	2.00	85.10	280	Ref. [6]

H_0 values and magnetic field ranges used in our study were preferred in terms of the computational stability of the model and simulation parameterization. Although coercivity values in the range of 18–159 kA/m for $CoFe_2O_4$ and 0.8–15 kA/m for Fe_3O_4 have been reported in the literature, the H_0 values used here were determined not from direct experimental measurements but by taking into account the numerical fit of the hyperbolic tangent-based model and the representativeness of the magnetic saturation behaviour. Therefore, the low H_0 and magnetic field limits chosen are suitable for the model to be able to show the trends comparatively. However, it is said that this suggestion will be evaluated in other studies, as additional simulations using higher ranges such as the recommended values may lead to higher energy loss.

The model proposed in this study successfully represents the magnetic saturation behaviour of Fe_3O_4 and $CoFe_2O_4$ nanoparticle composites. However, some improvements are necessary to increase the model's accuracy. One of these is to appropriately select the simulation parameters for the materials used. Another is to examine the temperature dependence of the coercivity field, as in the study by Mazeika et al. on $CoFe_2O_4$ and $CoFe_2O_4$/Polypyrrole samples [18]. This allows for more realistic predictions of hysteresis curves, taking into account both material hardness parameters and temperature effects. Another improvement would be to consider the effect of conductive polymers such as Polyaniline used in the work of Praveena et al. [19]. Considering the effects of aggregation-like behaviour of the doped nanoparticles in the matrix will also be important to increase the accuracy of the model, as discussed by Rana et al. [20]. Furthermore, in cases involving superparamagnetic inclusions, the use of the Langevin function will more accurately reflect magnetization changes, particularly in low-field regions [1,2,8]. Such additions will enhance the model's ability to capture the complex hysteresis behaviours reported in the literature.

IV. CONCLUSION

In this study, the magnetization properties and energy losses of Fe_3O_4 and $CoFe_2O_4$ composite materials doped with magnetic nanoparticles were investigated. Numerical integration methods such as Trapezoidal, Simpson 1/3, Simpson 3/8, and Newton-Cotes were used to analyze the magnetic hysteresis loops. The results show that the Newton-Cotes method provides the most accurate results, while the Trapezoidal and Simpson methods also yield close values. As the nanoparticle doping ratio increases, the magnetization values also increase. This confirms the effect of magnetic nanoparticles on the magnetic properties of the material. It was also found that energy losses vary for different materials depending on the nanoparticle doping ratio. Increasing the nanoparticle doping ratio leads to higher energy losses in magnetic materials. This can be explained by the widening of the magnetic hysteresis loops and the increase in the area between the magnetic field and magnetic flux density. The Simpson 1/3 method provides more precise results in energy loss calculations compared to the Trapezoidal method. This is because Simpson methods work with higher-degree polynomials and have lower error rates. When comparing the error rates of the numerical methods used, the Simpson 1/3 and Newton-Cotes methods exhibit lower error rates compared to the Trapezoidal method. In the study, it is shown that the Newton-Cotes method produces more accurate and reliable results, especially due to the higher degree polynomials used. It is also shown that the Newton-Cotes method is more effective in the integral calculations of complex magnetic hysteresis curves. These findings show that the Newton-Cotes and Simpson methods are more reliable in calculating energy losses in magnetic materials. Despite these advantages, the high computational cost of the Newton-Cotes method brings the Simpson 1/3 model to the fore in industrial design studies. Therefore, while the Newton-Cotes rule provides the highest accuracy in this study, Simpson's 1/3 rule can be preferred in terms of computational efficiency and precision for industrial designs.

However, discussing the model's potential applications, clearly stating its limitations, conducting comparative evaluations with different types of materials or commercial products, and outlining future research directions will increase the scope of the study and its relevance in industrial and academic contexts. Therefore, it is planned to include these elements in an expanded discussion section in the future.

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