

# Experimental and numerical analysis of the magnetic force applied to aluminum particles in an Eddy current separator

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## Abstract

This study presents a novel numerical model for predicting the magnetic force acting on spherical aluminum particles within an eddy current separator (ECS). The model considers key operational factors: rotational speed of the rotor, distance between particles and the rotor, and particle size. The model reveals a positive correlation between force and both particle size and rotor speed. Conversely, the distance between particles and the rotor exhibits a negative effect on the force. These relationships align with experimental observations, validating the model's accuracy. Beyond predicting force, this model holds significant potential for optimizing ECS operations. Moreover, the model developed can be utilized to estimate the rotational speed of the rotor and the distance between the particles and the rotor in alternative techniques, such as free-fall eddy current separators.

**Keywords:** Eddy current separation, experimental analysis, magnetic field, magnetic force, numerical simulation.

## 1. Introduction

Recycling non-ferrous metals such as scrap aluminum is a waste management strategy that converts these materials into usable products, helping to control and reduce pollution by reducing the amount of industrial and household waste. Metals extracted from ores are indistinguishable from those extracted from waste because their physical properties remain the same. This approach saves raw materials and reduces the need to extract them and the energy required for the process [1–3]. One of the most important advances in the recycling industry in recent decades was the introduction of eddy current separators [4, 5].

This technology is a reliable method for the selective sorting of non-ferrous metal particles in solid waste containing various substances [6–10]. In these types of separators, metal waste is exposed to a time-varying magnetic field. Ferrous and non-ferrous scrap are separated by inducing eddy currents in the non-ferrous particles, which then generate their own magnetic field that opposes the external magnetic field. As a result, non-ferrous metal particles are projected towards designated recycling containers under the influence of the magnetic force [11, 12]. Implementing this technology when sorting large pieces of scrap metal can significantly reduce separation costs.

In recent years, several separators based on this technology have been developed [13–19], including eddy current separators equipped with permanent magnets [20–23]. More recently, the influence of particle size [24] and form factor [25] on separation quality has been studied, Kadri *et al.* [26] developed a new vertical rotating disk of eddy current separator.

The main objective of this study is to develop a hybrid model capable of accurately predicting the force applied to spherical non-ferrous metallic particles, based on three factors: particle size, the distance between the particles and the permanent magnet rotor, and the rotor's rotational speed. The developed model is based

on the numerical calculation [27] of the induction in the area surrounding the rotor. The result obtained is used to calculate the approximate value of the force applied to the spherical particles. This approach will allow us to simulate the behavior of the particles in various configurations quickly and at a lower cost. By varying parameters such as particle size, rotor speed, the distance between the particles and the rotor, as well as the geometric parameters of the installation, it will be possible to obtain valuable insights into how these factors influence the separation process. This ultimately leads to clearer design choices and optimizations for real-world applications. The developed model is validated experimentally using a laboratory setup specifically designed for this study.

## 2. Electromagnetic modeling

The Fig. 1 presents the separator used in our study. This device allows for the separation of a flow into three categories of materials: ferrous metals, such as iron and steel, which contain iron and possess magnetic properties; non-ferrous metals, such as aluminum, copper, lead, and brass, which do not contain iron and are generally non-magnetic; and materials devoid of magnetic properties. When the mixture is deposited on the surface at the entrance of the conveyor belt (2), it is conveyed towards the permanent magnet drum (1). In this area, the non-ferrous metal particles, which are subjected to electromagnetic forces generated by the variable magnetic field induced by the rotation of the permanent magnet rotor, driven by the electric motor (3), are projected a greater distance than the non-conductive particles. The latter, which mainly include materials such as plastics, ceramics, and glass, do not react to the magnetic field and fall near the drum. Ferrous particles, on the other hand, remain attached to the surface of the conveyor belt and are thus transported to the collector located below the rotor [28-30]. This separation process effectively distinguishes non-ferrous metal particles from non-conductive materials while also facilitating the removal of ferrous particles (Fig. 2).

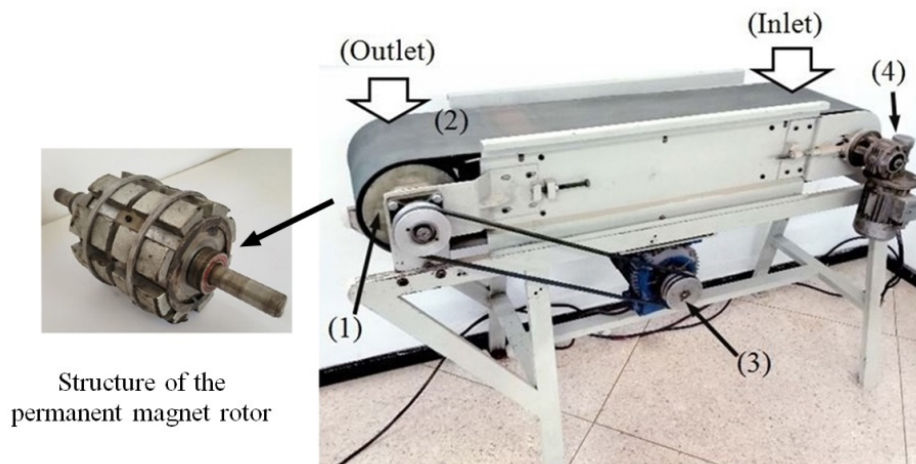


**Fig. 1.** Photograph of the Eddy current separator (ECS), (1) Magnetic drum with permanent magnets, (2) Conveyor belt, (3) Magnetic drum motor, (4) Conveyor belt motor.

To study the effect of the rotational speed of the permanent magnet rotor on the force applied to the particles, the drum of the conventional conveyor was replaced by a Teflon drum deposited coaxially on the shaft of the permanent magnet rotor using two ball bearings. This arrangement makes it possible to maintain the coaxiality of the rotor inside the drum during the separation process. It also allows the speed and direction of rotation of the permanent magnet rotor to be changed independently of the speed of the conveyor belt (2).

The eddy current separator examined here consists of a rotor equipped with four pairs of permanent magnets arranged around its circumference, exhibiting alternating polarity. The rotation of the rotor causes variations in the intensity and orientation of the magnetic field in the surrounding area. When a particle moves within this zone, it experiences changes in the intensity and orientation of the field due to its translational and rotational motion, as well as time-dependent variations caused by the rotation of the rotor. If we assume that the spatial variation of the field in the region occupied by the particle is negligible, the Lorentz force  $\vec{F}$  and the

torque  $\vec{T}$  generated by the eddy current in a spherical particle situated in the magnetic field can be expressed in terms of the magnetic moment [31]:

$$\vec{F} = V_p M_p \nabla B \quad (1)$$

$$\vec{T} = V_p \vec{M}_p \times \vec{B} \quad (2)$$

with  $M_p$  ( $A \cdot m^{-1}$ ) representing the magnetization of the particle and  $V_p$  ( $m^3$ ) denoting the volume of the particle.  $\nabla B$  ( $T \cdot m^{-1}$ ) is the gradient of the magnetic flux density at the position occupied by the particle.

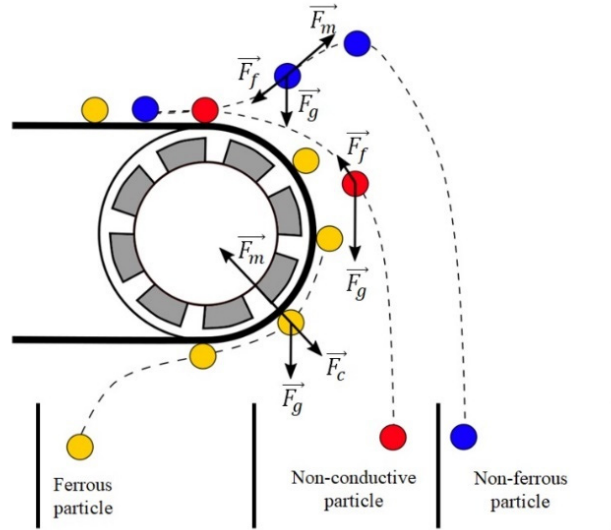


**Fig. 2.** Forces acting on ferrous, non-ferrous, and non-metallic particles in an eddy current separator.

Magnetic induction can be obtained by solving the partial differential equation of the magnetic vector potential  $A$  (Wb/m), which takes into account the induced current density in the conductive particle due to the magnetic field generated by the permanent magnet rotor [32].

$$\nabla^2 \vec{A} = -\mu \vec{J}_s + \sigma \mu \left( \frac{\partial \vec{A}}{\partial t} - \vec{V} \times \text{Rot}(\vec{A}) \right) - \text{Rot}(\vec{M}) \quad (3)$$

with  $\sigma$  ( $S \cdot m^{-1}$ ) and  $\mu$  ( $H \cdot m^{-1}$ ) representing respectively the conductivity and magnetic permeability of the particle,  $\vec{V}$  the velocity of the particle, and  $\vec{J}_s$  the induced current density in the particle.

In a cylindrical system ( $r, \theta, z$ ), the installation can be characterized by a magnetic potential vector that has only one component in the axial direction of the rotor [14]. If we also take into account the rotation of the particle at an angular speed  $\Omega$  (rad/s), the simplified model can take the following form:

$$\frac{\partial^2 \vec{A}}{\partial r^2} + \frac{1}{r} \frac{\partial \vec{A}}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \vec{A}}{\partial \theta^2} = -\mu \vec{J}_s + \sigma \mu \left( \frac{\partial \vec{A}}{\partial t} - \Omega r \frac{\partial \vec{A}}{\partial \theta} \right) - \frac{1}{r} \frac{\partial M_r}{\partial \theta} - \frac{M_\theta}{\partial r} - \frac{\partial M_\theta}{\partial r} \quad (4)$$

The resolution of the model for boundary conditions specific to the studied installation can lead to a solution represented by  $\vec{B}$  and  $\vec{M}$  defined in the  $(r, \theta)$  plane [32]. In a cylindrical coordinate system, the magnetic induction generated by the permanent magnet rotor can be estimated by an analytical model [33] represented by a Fourier series (eq. 5, eq. 6).

$$B_r = \sum_{n=0}^2 b_n (r/R_{drum})^{-(2n+1)k-1} \sin(2n+1)k(\theta - \omega_{drum}t) \quad (5)$$

$$B_\theta = \sum_{n=0}^2 -b_n (r/R_{drum})^{-(2n+1)k-1} \cos(2n+1)k(\theta - \omega_{drum}t) \quad (6)$$

with  $r$  (m) and  $\phi$  (rad) representing respectively the radial and angular position of the particle;  $R_{\text{drum}}$  (m) is the radius of the permanent magnet rotor;  $k$  is the number of pole pairs of the rotor; and  $\omega_{\text{drum}}$  ( $\text{rad s}^{-1}$ ) is the angular velocity of the permanent magnet rotor.

The use of the induction model (eq. 5 and eq. 6) requires experimental identification of the Fourier coefficients. Therefore, the model must be adapted to an existing installation, which can represent a weakness of this method. Another alternative can be used to estimate the value of the magnetic induction. This method is based on the numerical solution of the potential equation using the finite element method.

In a polar coordinate system, the boundary conditions associated with equation (4) of the magnetic vector potential are represented by the magnetic field  $B$  and the magnetization  $M$ , the value of which is imposed by the material of the magnets and the direction by their disposition on the rotor surface.

In the region defined by  $R_a \leq r \leq R_b$  (Fig. 3), the magnetization field  $M$  along the magnetic bars can be modeled by equation (7):

$$M(r, \theta) = \hat{r} \frac{M_a R_a}{r} \begin{cases} 1 & (\theta_0 \leq \theta \leq \theta_1) \\ 0 & (\theta_1 \leq \theta \leq \theta_2) \\ -1 & (\theta_2 \leq \theta \leq \theta_3) \\ 0 & (\theta_3 \leq \theta \leq \theta_4) \end{cases} \quad (7)$$

Where  $r$  and  $\theta$  are the radial and the angular coordinates with  $\theta_0 = 0$ ,  $\theta_1 = 30^\circ$ ,  $\theta_2 = 45^\circ$ ,  $\theta_3 = 75^\circ$ ,  $\theta_4 = 90^\circ$ ,  $\hat{r} = r / |r|$  is the radial unit vector,  $R_a = 75$  mm,  $R_b = 100$  mm are the inner and the outer radius of the rotor.

The space surrounding the magnetic rotor is limited by a circle of radius  $R$  (Fig. 3). A Neumann condition is applied to this limit to represent the continuity of the potential magnetic field.

$$\left. \frac{\partial A(r, \theta)}{\partial n} \right|_{r=R} = 0 \quad (8)$$

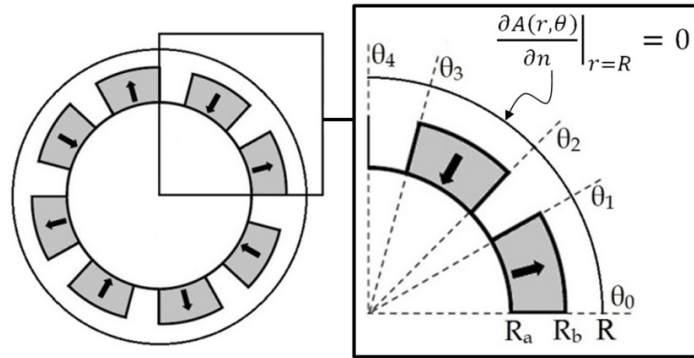


**Fig. 3.** Permanent magnet drum with alternating magnetization vector  $M$ .  
(Right) Unit cell of angular symmetry.

The installation rotor comprises 8 poles of neodymium-iron-boron (NdFeB) permanent magnets with an internal magnetization ( $M_a$ ) of the order of  $1.1 \times 10^6$  A  $\text{m}^{-1}$ . These magnets are positioned along the rotor's perimeter in an alternating pattern based on their polarity. The magnitude of the magnetic field  $B$  is derived from the magnetic vector potential by applying the numerical form of equation [32]:

$$\vec{B} = \text{Rot}(\vec{A}) \quad (9)$$

The numerical solution of equation (4) subject to the boundary conditions specified in equations (7 and 8) is shown in Fig. 4. This figure represents the magnetic vector potential lines (component  $\vec{A}_z$ ), It also shows the distribution of the magnetic field  $B$  in the plane perpendicular to the axis of the permanent magnet rotor.

The analysis of the intensity as well as the direction of the magnetic field has led to the definition of the active separation zone [34]. The variation of the components of magnetic induction as a function of time in this zone can take the form shown in Fig. 5.

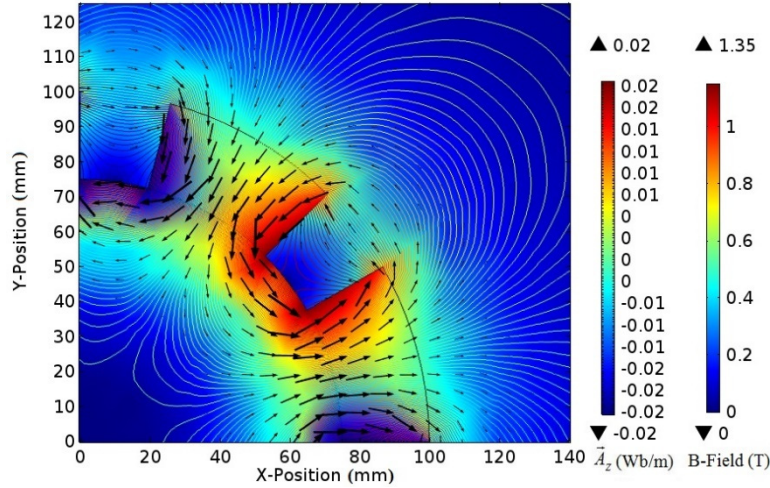


**Fig. 4.** Intensity and direction of the magnetic field B (T) with Magnetic vector potential lines; component  $\vec{A}_z$  (Wb/m) in the active zone of the separator.

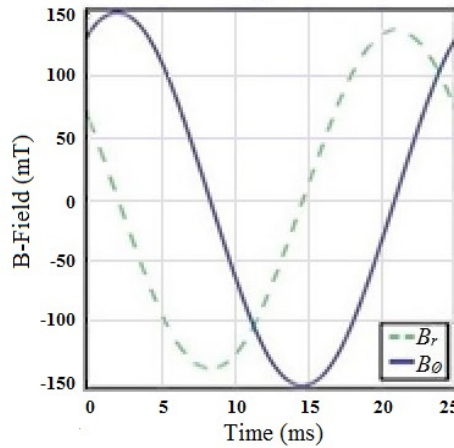


**Fig. 5.** Components of the magnetic induction B at the position (x, y) = (0, 132) mm above the magnetic drum rotating at 600 rpm.

The variation of the magnetic induction represented in this figure is obtained at a position (x, y) = (0, 132) mm above the rotor, which rotates clockwise at a speed of 600 rpm.

Once the solution is obtained, the radial force, tangential force, and torque applied to a particle located in the magnetic field area can be estimated by the equations (10,11 and 12) [14].

$$F_r = \frac{k+1}{r} \frac{|B|^2 V}{\mu_0} R(\mu_0(k\omega_d + \Omega)\sigma d^2) \quad (10)$$

$$F_t = \frac{k+1}{r} \frac{|B|^2 V}{\mu_0} I(\mu_0(k\omega_d + \Omega)\sigma d^2) \quad (11)$$

$$T = -\frac{|B|^2 V}{\mu_0} I(\mu_0(k\omega_d + \Omega)\sigma d^2) \quad (12)$$

with  $F_r$ ,  $F_t$ , and  $T$  representing the radial force, tangential force, and magnetic torque applied to a spherical particle with a diameter  $d$  (m), a volume  $V_p$  (m<sup>3</sup>), and a conductivity  $\sigma$  (S m<sup>-1</sup>), experiencing an angular rotation speed  $\Omega$  (rad s<sup>-1</sup>),  $\mu_0$  ( $4\pi \times 10^{-7}$  H m<sup>-1</sup>) being the magnetic permeability of free space.  $R(\delta)$  and  $I(\delta)$  are two functions that depend on the shape and orientation of the particle.

$$R(\delta) = \frac{21 \delta^2}{20(1764 + \delta^2)} \quad (13)$$

$$I(\delta) = \frac{882 \delta}{20(1764 + \delta^2)} \quad (14)$$

### 3. Experimental validation

To validate our simulation model, we proceeded with experiments to measure the radial component of the magnetic force exerted on the particle. The semi-industrial eddy current separator used in this study (Fig. 6) consists of two drums carrying a conveyor belt, the latter being generally moved by the rear steel drum. The non-metallic front drum contains a fast rotating magnetic system. Permanent magnets are arranged, with alternating polarity, along the circumference of the magnetic system. The separator has 8 poles rotating at speeds of up to 3000 rpm. This system generates alternating magnetic fields, resulting in strong eddy currents in the non-ferrous conductive metal parts, which in turn create their own magnetic fields in opposition to the external fields. The non-ferrous parts are deviated and projected into a recovery collector.

Fig. 6 shows the experimental installation used. The system consists of the semi-industrial eddy current separator described above, a high-resolution PASPORT PASCO PS-2189 force sensor connected to a computer via the Universal Interface 850 PASCO UI-5000 using PASCO Capstone software for data collection and analysis. Additionally, a LUTRON DT-2236 digital contact and reflection tachometer was used to measure the rotational speed of the permanent magnet rotor. Experiments were carried out with three spherical aluminum particles of diameters 20 mm, 25 mm and 30 mm.

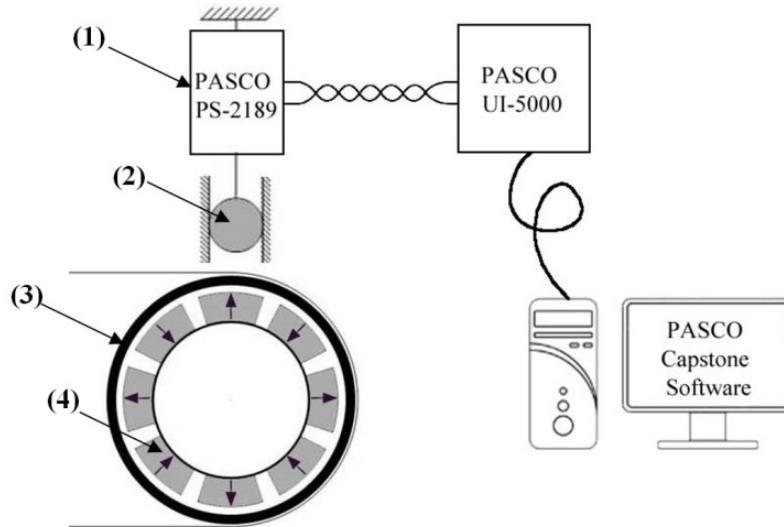


**Fig. 6.** Descriptive schematic of the experimental setup; (1) Force sensor connected to a computer; (2) aluminum particle; (3) Teflon drum; (4) permanent magnet rotor.

The factors that have been considered are: 1) the rotation speed of the magnetic drum (rpm) controlled by a three-phase autotransformer and visualized by a digital tachometer; 2) the distance between the magnetic drum and the particle (mm); 3) the size of the particle (mm). To carry out the experiment, the particle is suspended from a non-metallic support mechanically connected to the force transducer. This support is long enough to ensure that field variation does not affect the measuring instrument. The two non-metallic bars guide the particle in a purely vertical movement to prevent it from oscillating. This enables precise measurement of the magnetic force applied to the particle. The force sensor -particle assembly is then positioned at different distances above the magnetic drum. A maximum value of the force, representing the vertical alignment of the particle's center with the center of the cylinder, was experimentally determined by adjusting the horizontal position of the particle above the rotor, which rotates at a constant speed.

The distance between the particle and the magnetic drum is then progressively adjusted in 5 mm steps, in a range from 10 mm to 180 mm. All experiments were repeated twice, and the mean value was retained.

Fig. 7 displays the experimental results, representing the variation of the radial magnetic force component exerted on two aluminum spheres measuring 20 and 30 mm in diameter. The measured values are represented by the black points, while the surface corresponds to the value predicted by a regression model.

The surface represents the amplitude of the force exerted on the particles as a function of two variables: the rotation speed of the rotor of the permanent magnet measured in rpm and the distance between the particles and the rotor measured in (mm). The results indicate a significant increase in magnetic force when the particle approaches the surface of the permanent magnet rotor. This force becomes much more important when the rotation speed of the rotor increases. It also appears from these results that the magnetic force exerted on the 30mm diameter particle (Fig. 7(b)) is greater than the one exerted on the 20mm diameter particle (Fig. 7 (a)), this is explained by the increase of the induced current in the particles which is proportional to their size.

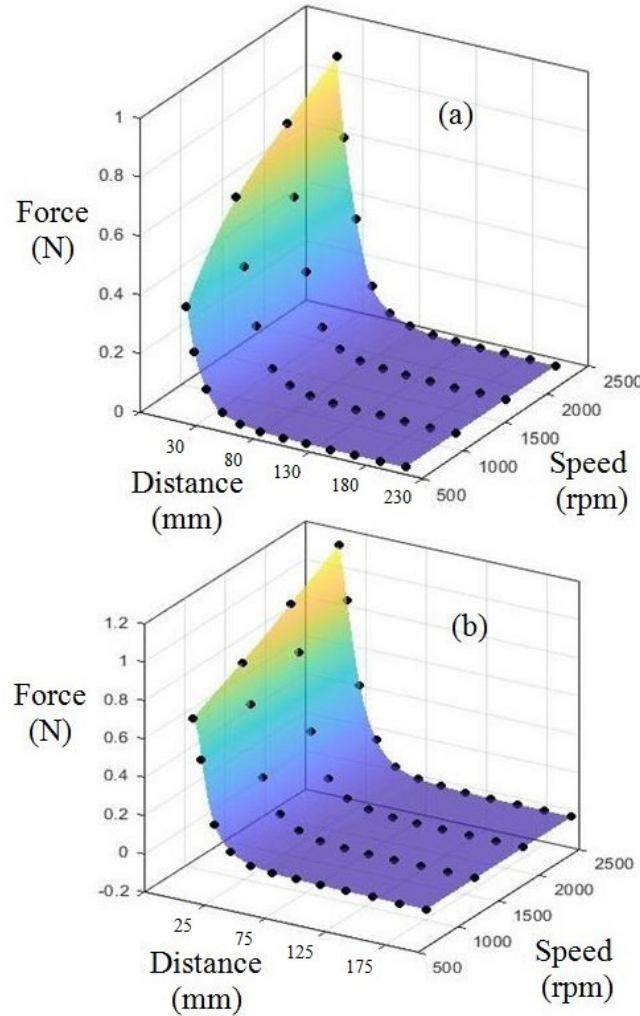


**Fig. 7.** The experimental value of the magnetic force exerted on aluminum particles having a diameter of (a)  $D = 20$  mm; (b)  $D = 30$  mm.

According to these results, we can say that the Foucault current separation process depends mainly on the intensity of the magnetic field, the size of the particles as well as the speed of rotation of the drum. These parameters considerably influence the intensity of the magnetic force applied to the particles to be separated.

A comparison between the results obtained by the numerical model and those obtained experimentally is represented in Fig. 8. For the two particles ( $D1 = 20$  mm and  $D2 = 30$  mm), the rotation speed of the magnetic rotor is set to 600 rpm. This comparison shows the presence of a concordance greater than 95% between the results obtained by simulation and those obtained experimentally (15).

$$Deg (\%) = 1 - \frac{\sum_{i=1}^N (\hat{y}_i - y_i)^2}{\sum_{i=1}^N [|\hat{y}_i - \bar{y}| - |y_i - \bar{y}|]^2} \quad (15)$$

where  $\hat{y}_i$  is the force predicted by the numerical model,  $y_i$  is the experimentally measured force, and  $\bar{y}$  is the average forces predicted by the numerical model.

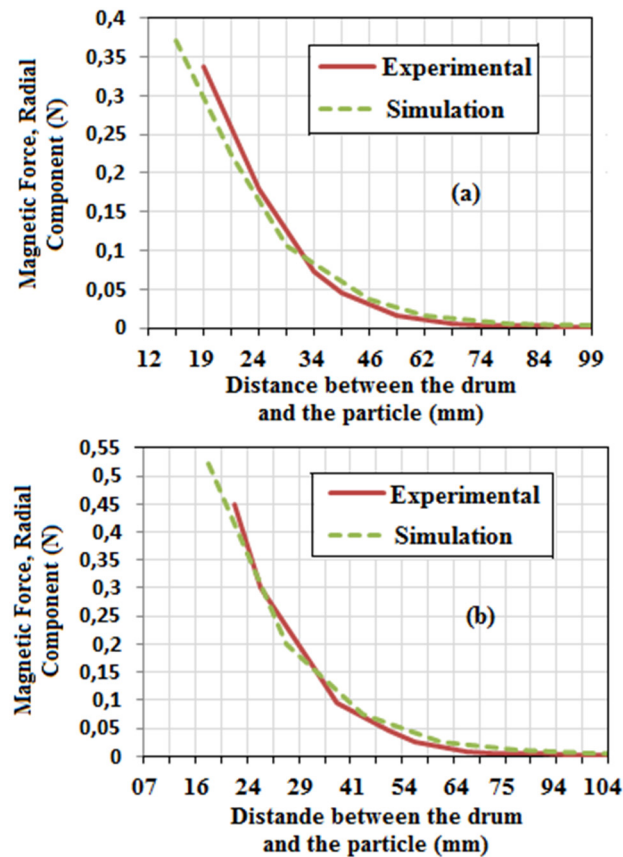


**Fig. 8.** Comparison of the results obtained by simulation with those obtained experimentally; (a)  $D = 20$  mm; (b)  $D = 30$  mm.

#### 4. Conclusion

In this study, the magnetic force applied to non-ferrous metallic particles in the presence of a variable magnetic field was examined using a numerical model based on the finite element method. This two-dimensional model functions as a black box, taking the rotational speed of the rotor, particle size, and distance between the rotor and particle as inputs and providing an estimate of the intensity of the electromagnetic force applied to the particle as output. By using this model, we were able to predict the electromagnetic behavior of the system and its effects on the particles.

The results from the model highlight the importance of considering the rotation speed of the permanent magnet rotor and the size of the particles for separating ferrous and non-ferrous metals in a Foucault current separator. In industrial applications, reducing the size of waste is crucial to ensure proper dissociation of ferrous and non-ferrous materials before separation in a Foucault current separator. However, excessively reducing the waste size can lead to a decrease in the efficiency of the separator.

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