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Effect of Permanent Magnet Arrangement on the Efficiency of a Horizontal Drum Eddy Current Magnetic Separator

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Abstract

The aim of this study is to investigate the effect of permanent magnet arrangements on the efficiency of an eddy current magnetic separator. Such a separator consists mainly of a drum equipped with identical NdFeB permanent magnet bars, with a residual magnetic flux density (Br) of 1.1 T, and a conveyor belt that transports the material to be purified. Through numerical simulations of various magnet configurations, we studied how these arrangements influence the magnetic field distribution, the Lorentz force acting on the particles and the resulting trajectories of conducting particles, which collectively reflect the separation efficiency. To accomplish this, the magnetic field and the conductive piece dynamic governing equations were numerically solved by coupling the finite element (FE) and Runge Kutta (RK4) methods. The results show that optimizing the magnetic field, especially through a HALBACH-type configuration, can significantly enhance separation efficiency by improving the capture of non-ferrous particles.

Keywords

drum, eddy current, finite element, Halbach array, permanent magnets

1 Introduction

Eddy current separation (ECS) is an extensively employed technique in the scrap recycling industry used for the recovery and purification of conductive non-ferrous metals, such as copper (Cu), aluminium (Al), and lead (Pb), as well as for the separation of different types of non-ferrous metals from one another [1, 2]. Its principle is based on the induction of eddy currents in non-ferrous metal particles when they are exposed to a changing magnetic field generated by a rotating drum equipped with strong permanent magnets. These eddy currents create an opposing magnetic field, producing a repulsive force (Lorentz force) [3], which ejects the non-ferrous metal particles away from the drum. Several studies have been devoted to the comprehensive investigation of the effect of various parameters on the efficiency of separation processes. These parameters include particle size [4], particle shape and conductivity-to-density ratio (σ/ρ) [5], poles number [6], feeding, roller, and conveyor belt speeds [7], speed difference between the conveyer belt and the magnetic drum [8] and non-ferrous material particles temperature [9].

The permanent magnet array configuration of the magnetic drum has a strong influence on the magnetic field distribution [10]. In this context, the study reported in Belounis and Belguet [10] used a static Halbach-configured drum separator to enhance the separation efficiency of ferromagnetic particles.

In this work, a comparative analysis was performed on the efficiency of an eddy current separator using a drum with Halbach arrangement versus a conventional alternating N–S–N arrangement of permanent magnets (see Figs. 1 and 2). The objective was to study the influence of the permanent magnet arrangements on the separation

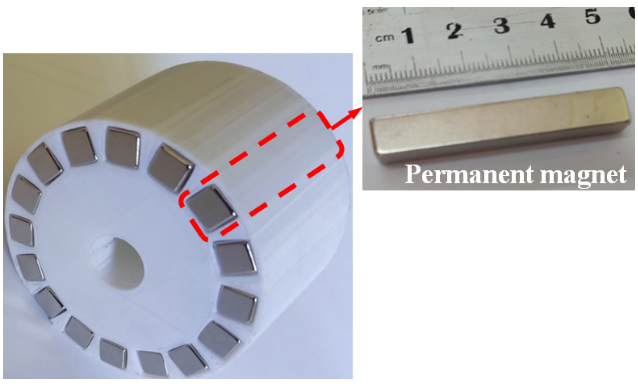

Fig. 1 Magnetic drum used for eddy current separator

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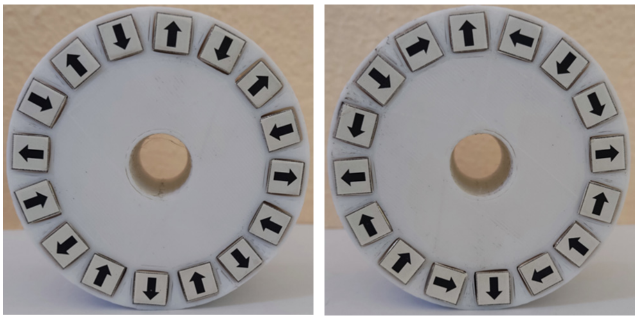


(a) (b)

Fig. 2 Configurations of the drum: (a) Conventional alternating N–S–N configuration; (b) Halbach configuration

efficiency. Such a study was based on the computation of conductive particle trajectories, which allows for the knowledge of the final position of the particles (repulsion distance) and, consequently, the separation efficiency. To compute the particle final repulsion distance, the magnetic field and the particle dynamic governing equations were solved by coupling the numerical finite element (FE) and fourth order Runge Kutta (RK4) methods in a 2D configuration. The obtained results show that using a Halbach arrangement in such a way that the field is increased outside the drum improves the efficiency.

2 Modeling of the magnetic separation problem

To allow the deflection of conductive particles, a time-varying magnetic field is required. To compute the distribution of such strongly evolving field in the used separator, we solved the governing equation given by [11]:

$$\vec{\nabla}\times\left(\frac{1}{\mu}\left(\vec{\nabla}\times\vec{A}\right)\right)+\sigma\left(\frac{\partial\vec{A}}{\partial t}-\left(\vec{v}_p\times\vec{B}\right)\right)=\frac{1}{\mu}\left(\vec{\nabla}\times\vec{B}_r\right). \quad (1)$$

where $\vec{\nabla}$ is the Nabla-Operator, $\vec{A}$ is the magnetic vector potential, $\vec{B}$ is the magnetic flux density, $\vec{B}_r$ is the residual magnetic flux density of the magnets, μ is the magnetic permeability, σ and $\vec{v}_p$ are respectively, the particle's electrical conductivity and velocity.

The magnetic force applied on the conductive particle contains two components. The first is related to the locally time variations of the applied field and the second is related to the particle displacement. The resulting force is then expressed as follows [12]:

$$\vec{F}_L=-\sigma\left(\frac{\partial\vec{A}}{\partial t}-\left(\vec{v}_p\times\vec{B}\right)\right)\times\vec{B}. \quad (2)$$

The conducting particle trajectory is computed by solving the dynamic equation established according to the dynamic principle (Newton formula):

$$m_p\frac{\partial\vec{v}_p}{\partial t}=\sum\vec{F}. \quad (3)$$

where m_p is the particle mass and $\vec{F}$ is the resultant of the applied forces.

3 Computed results

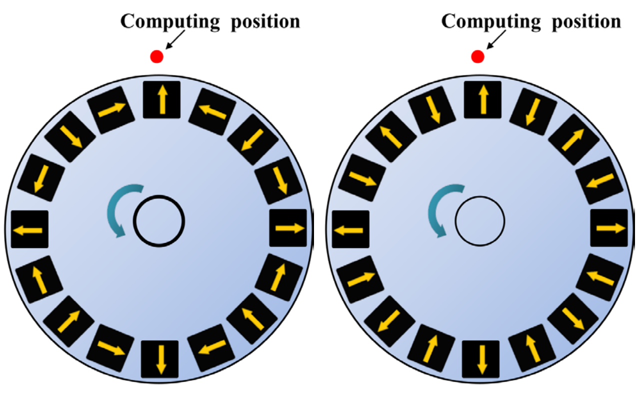
3.1 Generated magnetic field

To permit a deflection of conductive particles, a time-varying magnetic field must be applied. To generate this field, we used a drum of nonmagnetic material equipped with a circular arrangement of sixteen NdFeB identical magnets of size 9 × 9 × 50 mm^3 and B_r = 1.1 T periodically distanced by an angle of 22.5°. To verify the alternative nature of the applied magnetic field, we calculated and plotted the variations of the magnetic field through the magnetic vector potential at a specific point situated in the separation zone (see Fig. 3). For the two aforementioned drums rotating counterclockwise at 1500 rpm, the computed magnetic vector potential in a position located at 5mm away from the drum's perimeter is shown in Fig. 4.

Fig. 4 shows that the magnetic field generated by the two configurations has a perfectly sinusoidal nature, allowing the repulsion of conducting particles away from the drum.

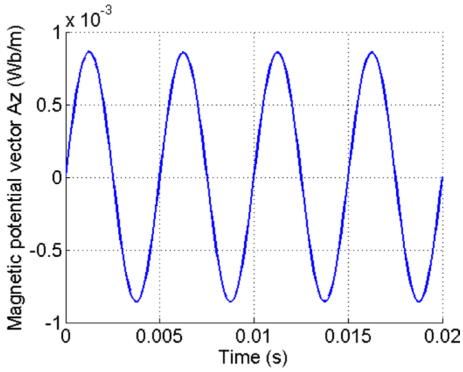
The spatial distribution of the magnetic induction is crucial for identifying regions of high intensity, which correspond to areas where the magnetic force is concentrated. For this reason, the magnetic induction distribution is systematically presented at the beginning of the results section for each simulation. The magnetic problem was solved for the configurations shown in Fig. 3, yielding the results presented in Fig. 5.

Fig. 5 shows that the Halbach configuration enhances the magnetic field distribution by concentrating the magnetic flux density in the external region of the drum (Zone 2),



(a) (b)

Fig. 3 Considered drums and computing position: (a) Halbach configuration; (b) Alternating N–S–N configuration



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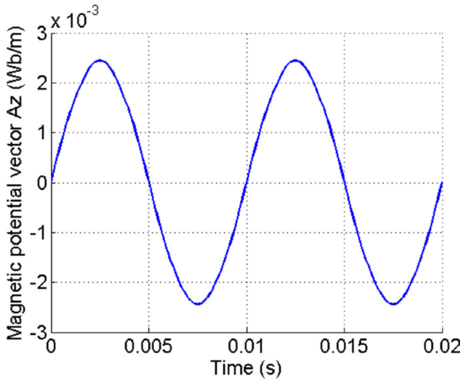

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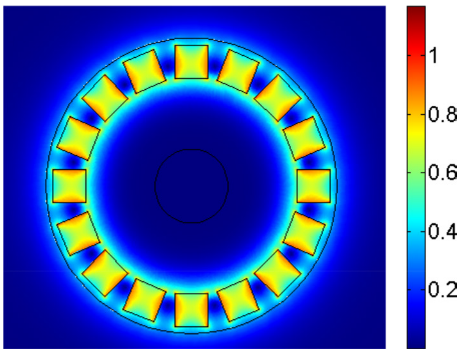
Fig. 4 Variations of the magnetic vector potential as a function of time: (a) Alternating N–S–N configuration; (b) Halbach configuration



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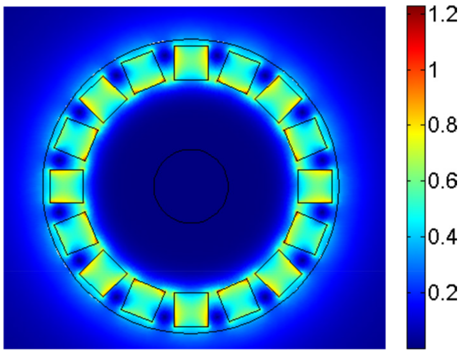


(b)

Fig. 5 Distribution of the magnetic flux density: (a) Alternating N–S–N configuration; (b) Halbach configuration

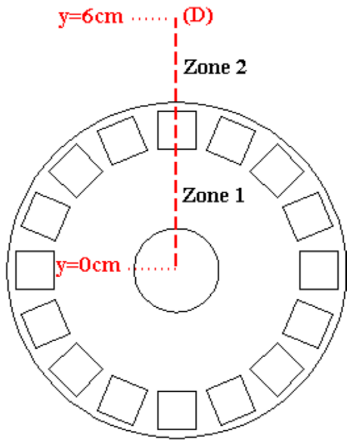
where the separation process occurs, while significantly reducing it inside the drum (Zone 1).

To better illustrate the results presented above, Fig. 6 presents the variation of the magnetic flux density along a vertical line (D) crossing both regions (see Fig. 6 (a)).

Fig. 6 confirms that the Halbach arrangement reduces the magnetic induction in Zone 1 and increases it in Zone 2.

To quantitatively evaluate the distribution of the generated magnetic field in the separation zone, we computed and presented the variations of the magnetic flux density along the length of the line (M) situated at a fixed distance y_0 = 5 mm away from the perimeter of the drum (see Fig. 7 (a)).

The results of Fig. 7 show that the magnetic induction produced by the Halbach configuration is higher than that generated by the conventional alternating N–S–N configuration, which has permitted the extension of the separation zone. The separation effect can be observed at a distance of 8 cm from the center of the drum, compared to 5 cm for the N–S–N configuration. These findings indicate that the Halbach configuration can significantly improve the separation efficiency.



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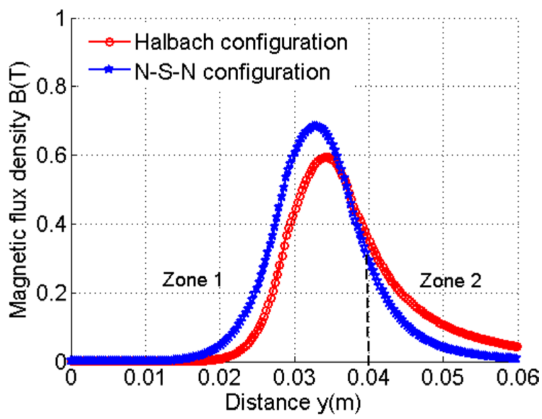

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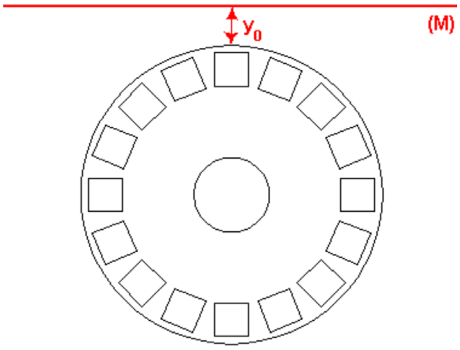
Fig. 6 Evaluation of the magnetic flux density along line (D): (a) The computing line; (b) Variation of the magnitude of the magnetic flux density along the length of the line (D)



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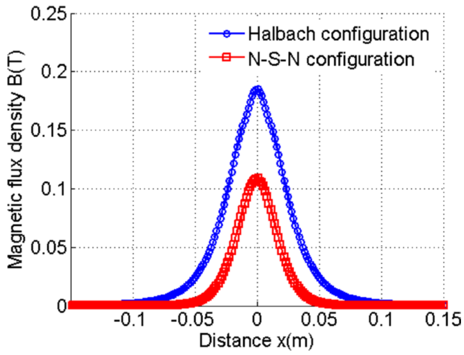
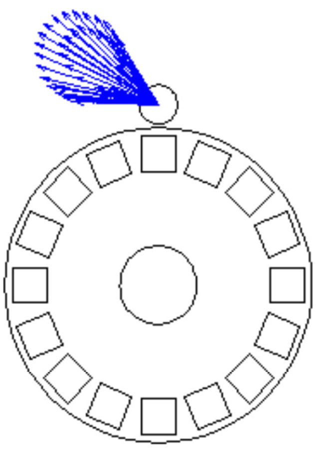


(b)

Fig. 7 Variation of the magnetic flux density along of the length of the line (M): (a) the computing line; (b) magnetic flux density B

3.2 Distribution of the magnetic force

The Lorentz force applied to the conducting particles is computed as a function of the particle displacement by evaluating, at each time step, the magnetic induction and the density of the induced current at the particle locality. To show the repulsive nature of such a force, we present in Fig. 8 the evolution of the resultant force vector obtained for a complete rotation of the drum.



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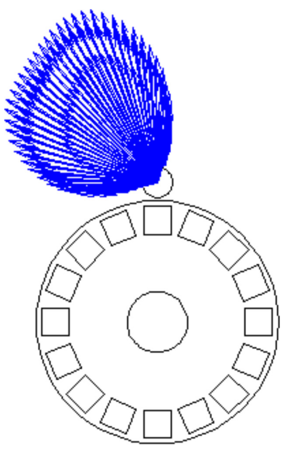


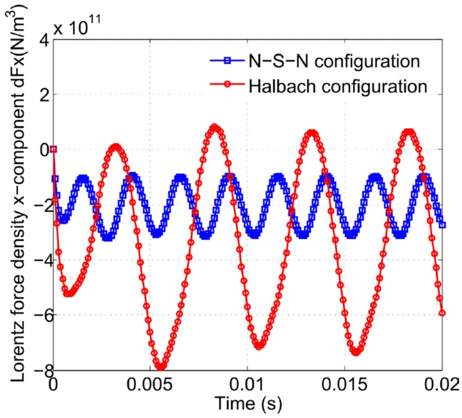
(b)

Fig. 8 Evolution of the Lorentz force applied to a circular conductive particle of radius 0.5 cm and conductivity $\sigma = 5\ e^7$ S/m positioned at 5 mm above the drum's perimeter, for a complete rotation of the drum: (a) N–S–N configuration; (b) Halbach configuration

Fig. 8 shows that all the force vectors are oriented towards the outside of the drum, which means that it is always repulsive.

To allow for a quantitative comparison, we have evaluated the variations of the three components of the force density applied to the particles as a function of time for the two drum configurations. The obtained results are shown in Fig. 9.

Fig. 9 shows that the amplitude of the force generated by the Halbach configuration is greater than that produced



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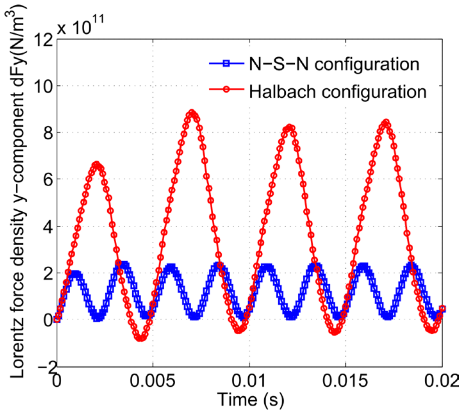

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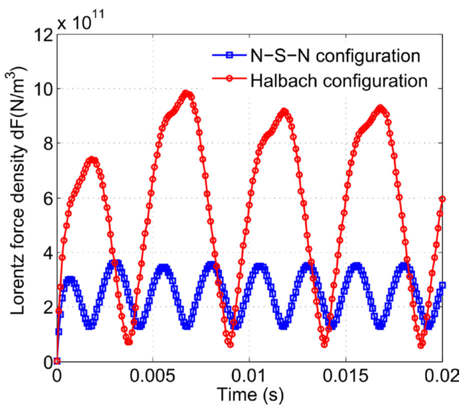

(c)

Fig. 9 Variation of the Lorentz force density applied to the particle as a function of time: (a) x-component dF_x; (b) y-component dF_y; (c) magnitude dF by the conventional alternating N–S–N configuration, which permits a larger separation distance.

3.3 Particle trajectory

To verify the possibility of separation of conducting particles and to estimate the effect the arrangement of the magnets on the separation final position (repulsion position) and, consequently, on the efficiency of the separation, we have computed and presented the particle trajectories for the two considered configurations. The resolution of Eq. (3) for the previously cited drum parameters and rectangular particle of size 3 × 3 × 0.1 cm^3 and conductivity $\sigma = 5.10^7$ S/m has given the results of Fig. 10 for a drum rotation speed $N = 1000$ rpm and $N = 1500$ rpm.

For better clarity, we present in Table 1 the particle final positions related to the considered configurations.

The results of Fig. 10 and Table 1 show clearly that the final separation position depends on the drum configuration. The repulsion distances obtained with the Halbach configuration are greater than those obtained with the conventional alternating N–S–N configuration. This indicates that the separation efficiency can be enhanced by using a drum with a Halbach arrangement of permanent magnets.

4 Conclusion

This study investigated the impact of the permanent magnet arrangement on the separation efficiency of a horizontal eddy current separator dedicated to the separation of conducting particles. Our analysis was based on the calculation of the conducting particle trajectories, which allowed us to determine the final ejection position reflecting the separation efficiency. To achieve this, two configurations were studied and compared: the Halbach array and a conventional alternating N–S–N arrangement. The results show clearly that the use of a Halbach array can significantly improve the separation efficiency compared to the conventional N–S–N arrangement, offering valuable insights for optimizing separation processes.

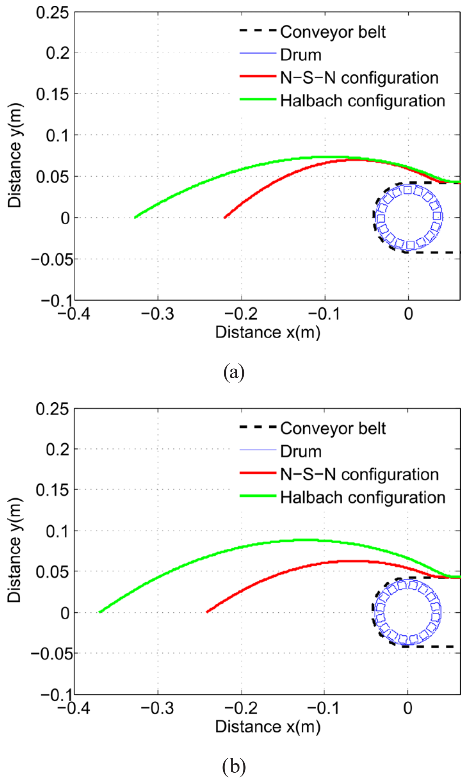

Fig. 10 Particle trajectories: (a) $N = 1000$ rpm; (b) $N = 1500$ rpm

Table 1 Ejection distances of conducting particle

Configuration		Halbach	Alternating N–S–N
X (cm)	$N = 1000$ rpm	32.85	22.08
	$N = 1500$ rpm	36.82	23.87

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