https://doi.org/10.3311/PPee.42122

Periodica Polytechnica Electrical Engineering and Computer Science, 69(4), pp. 428–433, 2025

Study of the Design of a Drum Separator Using Halbach Array Magnets for the Removal of Fine Iron Particles

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Received: 03 September 2025, Accepted: 04 December 2025, Published online: 12 December 2025

Abstract

The aim of this paper is to study the possibility of use of the Halbach array magnets in the design of a magnetic drum separator and to address their performance and efficiency in removing fine iron particles transported by conveyor belt. Such a study is based on the estimation and comparison between the particle capture efficiencies of two configurations of the drum separator, one designed by using conventional arrangement of magnets and other based on the use of Halbach array magnets. To check the capture efficiency, we computed the particle trajectory. For this, we solved numerically the magnetic and particle dynamic governing equations by coupling the finite element (FE) and Runge–Kutta (RK4) methods. The obtained results show that the Halbach configuration can give better capture performance.

Keywords

drum magnetic separator, fine particle, Halbach array, finite-element, particle trajectory, numerical simulation

1 Introduction

Magnetic separation is a technique based on the application of a magnetic field to separate, sort or concentrate minerals. It is used in several industrial domains, including the extraction of metals from mines, metal waste sorting and recycling centers, purification processes for liquids, gases and consumer products [1–8].

To design a powerful separator capable to extract fine iron particles of relative magnetic permeability $\mu_{rp} \leq 40$, we propose in this work a study of the interest of the use of a configuration of Halbach array magnets intended for the removal of micrometric iron particles. In the considered separator, the material to be treated is transported by a conveyor belt trained at a given speed (see Fig. 1).

The Halbach array magnet is a permanent multipole magnets realized by Klaus Halbach [9]. It is made up of a set of permanent magnets arranged and placed with different directions of polarity (see Fig. 2) [10–14]. In our case, the proposed Halbach array magnets consists of seven NdFeB magnets with residual magnetic flux density $B_r = 1.1$ T, relative permeability $\mu_{rm} \approx 1$, cross section 1 cm^2 and the polarity directions as shown in Fig. 1 (b).

To estimate and verify the performance of the new separator, we compared between the capture efficiencies of particle for the proposed Halbach array configuration and a conventional configuration based on the use of three permanent magnets which the same characteristics (see Fig. 1(a)). To carry out this comparison, we computed and analyzed the distribution of the magnetic force in the vicinity of the drum and the particle trajectories. For this, we solved a coupled system of the governing equations of the particle dynamics and magnetic field problems.

To take into account the geometrical complexity and dynamic equation non linearity, a numerical resolution based on the coupling of the finite element (FE) and Runge-Kutta (RK4) methods was achieved [15–17].

2 Mathematical formulations

The mathematical modeling of drum magnetic separation processes allows the study of particle behavior under the combined effects of the magnetic field, gravity, and centrifugal forces. These particles are subjected to several forces: magnetic, gravitational, and centrifugal. In our study, the friction force between the particles and the conveyor belt was considered negligible due to the high speed of the drum, which reduces the contact time, and the fineness of the particles, which limits the contact surfaces.

Cite this article as: Belounis, A., Belguet, O. "Study of the Design of a Drum Separator Using Halbach Array Magnets for the Removal of Fine Iron Particles", Periodica Polytechnica Electrical Engineering and Computer Science, 69(4), pp. 428–433, 2025. https://doi.org/10.3311/PPee.42122

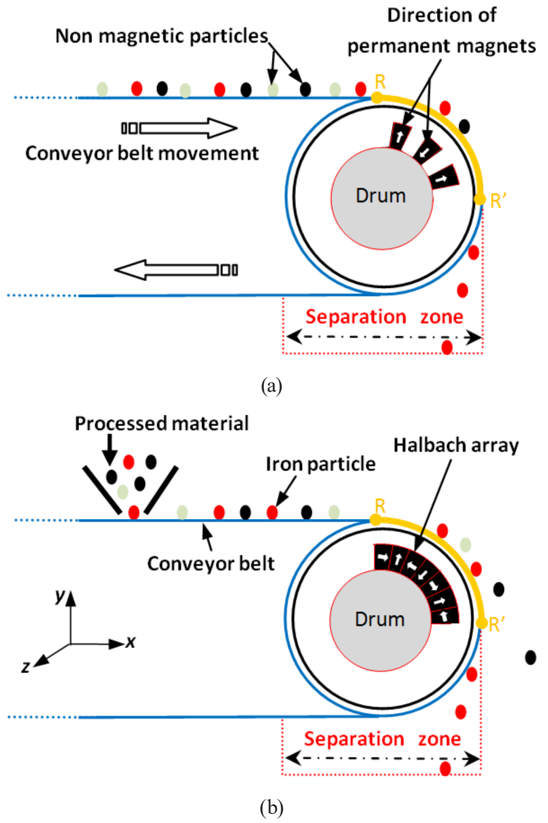


Fig. 1 Two dimension view of the proposed magnet drum separator: (a) Conventional three permanent magnets configuration; (b) Proposed Halbach array configuration

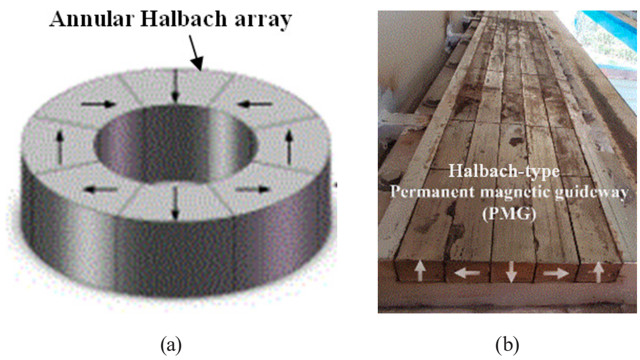


Fig. 2 Different Halbach array magnets configurations: (a) Annular Halbach array; (b) Halbach-type permanent magnetic guide way using in maglev trains [10–14]

2.1 Applied magnetic field

In the studied separator, the magnetic field is generated by static permanent magnets. Therefore, the distribution of such a field is governed by the mathematical model expressed by [16, 17]:

$$\vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{A} \right) = \frac{1}{\mu} \vec{\nabla} \times \vec{B}_r . \tag{1}$$

In Eq. (1) $\vec{A}$ is the magnetic vector potential, μ is the magnetic permeability and $\vec{B}_r$ is the magnets residual flux density.

2.2 Acting forces and dynamic equation

In the separation process of iron particles, the particles are mainly subjected to the magnetic and gravitational forces given by [16, 18]:

$$\vec{F}_m = \mu_0 V_p \left(\vec{M} \cdot \vec{\nabla} \right) \vec{H}, \tag{2}$$

$$\vec{F}_g = m \vec{g}, \tag{3}$$

where $\vec{M}$ is the particle magnetization, $\vec{H}$ is the magnetic field strength, V_p is the particle volume, m is the particle mass and $\vec{g}$ is the gravity acceleration.

As a function of the two considered forces, the particle dynamic equation is then given by [19–21]:

$$m \frac{d\vec{v}_p}{dt} = \vec{F}_m + \vec{F}_g . \tag{4}$$

In Eq. (4) $\vec{v}_p$ the particle velocity.

3 Results and discussion

In our resolution, we opted for a two-dimensional (2D) approach, which significantly reduces computational time and costs while minimizing uncertainties associated with three-dimensional discretization. This simplification is justified by the geometry of the structure under study, which has sufficient length in the out-of-plane direction (axis of invariance in 2D).

This assumption can be validated through a comparative study between a simplified 3D model and the 2D model, allowing, for example, the evaluation of the quality of the magnetic flux density variation in a region of interest [16]. Under these conditions, edge effects can be considered negligible.

In this analysis, we assumed that the particles have a negligible influence on the overall magnetic field distribution, due to their moderate permeability ($\mu_r \leq 40$), very small size (approximately 1 μm^3), and low concentration. Consequently, the magnetic field can be considered effectively independent of the particle configuration, allowing the field calculation and the force computation to be treated separately.

Before presenting and discussing the results, it is useful to summarize the calculation parameters in Table 1.

3.1 Magnetic field and magnetic flux density

To verify the correctness and validity of the governing equation for the magnetic problem and the developed computational program, we first calculated the magnetic field distribution, expressed through the magnetic vector potential, within the separation zone. This step ensured

Table 1 Physical and geometric computational parameters

Parameters	Values
Residual magnetic flux density of magnets (B_r) (T)	1.1
Relative permeability of magnets (μ_{rm})	1
Vacuum permeability (μ_0) (H/m)	$4\pi \times 10^{-7}$
3D dimension of magnet (mm)	11 × 10 × 100
Relative permeability of particles (μ_{rp})	40
Size of cubic particles (m)	$10^{-6} \times 10^{-6} \times 10^{-6}$
Gravity acceleration (m/s^2)	10
Iron density (kg/m^3)	7860
Drum radius (m)	6.5×10^{-2}

that both the theoretical model and the numerical implementation produced consistent and reliable results.

The results corresponding to the two configurations under study, namely the Halbach and conventional arrangements, are presented in Fig. 3 (a) and (b).

In Fig. 3, we see that the distribution of the magnetic vector potential is periodic and symmetric which perfectly corresponds to the chosen polarity of the magnets.

Fig. 3 (b) shows a strong concentration of the field at the auxiliary magnets. Also the Halbach array configuration can with the chosen arrangement of the magnets generate a quasi-homogeneous field.

Fig. 4 shows that the intensity of the magnetic flux density generated by the Halbach array configuration is greater than that given by the three permanent magnets conventional configuration.

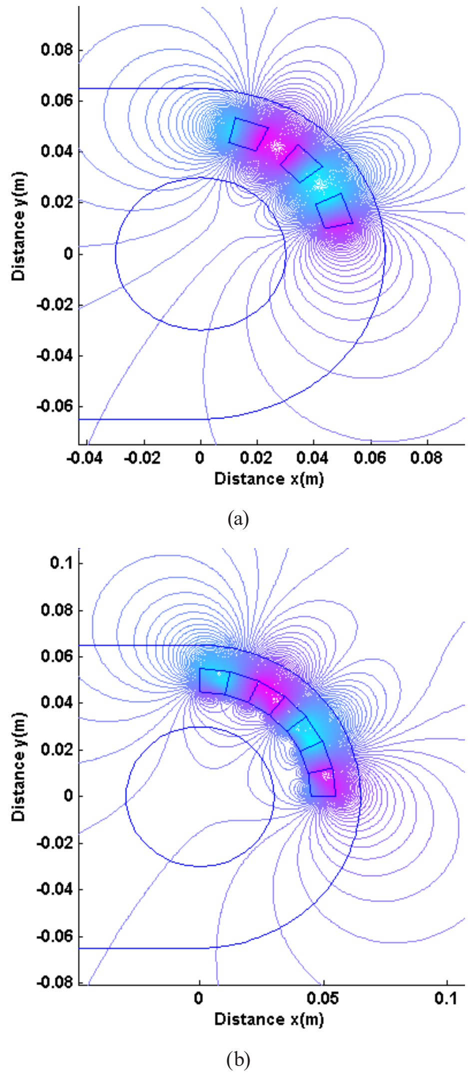


Fig. 3 Distributions of the magnetic vector potential in the vicinity of the drum: (a) Conventional 3 permanent magnets; (b) Halbach array magnets

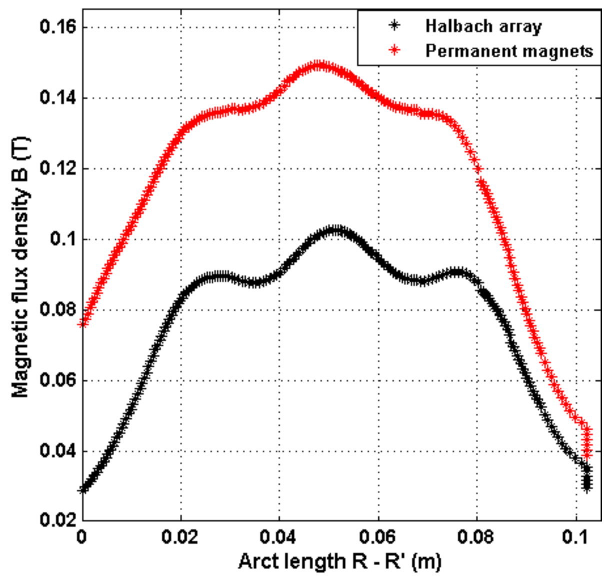


Fig. 4 Variations of the magnitude of the magnetic flux density along the distance *R*–*R′* (see Fig. 1)

3.2 Applied magnetic force density

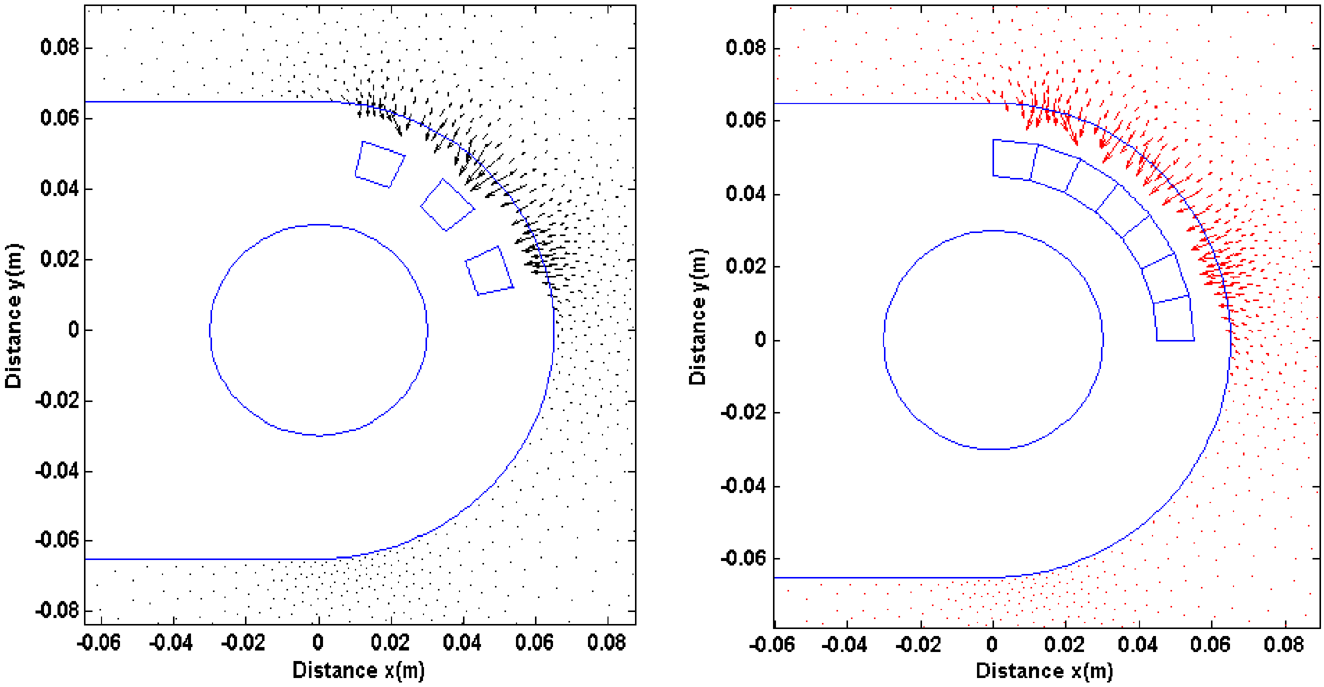
In Fig. 5 (a) and (b), we present the distribution of the magnetic force in the useful region of the study domain, which permits to check the possibility of particle separation. To verify the previous finding about the interest of the Halbach array configuration, we also present the variation of the magnetic force along the distance *R*–*R′* for the two studied configurations.

In Fig. 5, we see clearly that the force directed towards the permanent magnets, which means that if a particle passes in this region it may be captured.

Fig. 6 shows that similarly to that seen previously for the magnetic flux density the Halbach array configuration gives very important magnetic force near the magnets compared to that obtained by the conventional one.

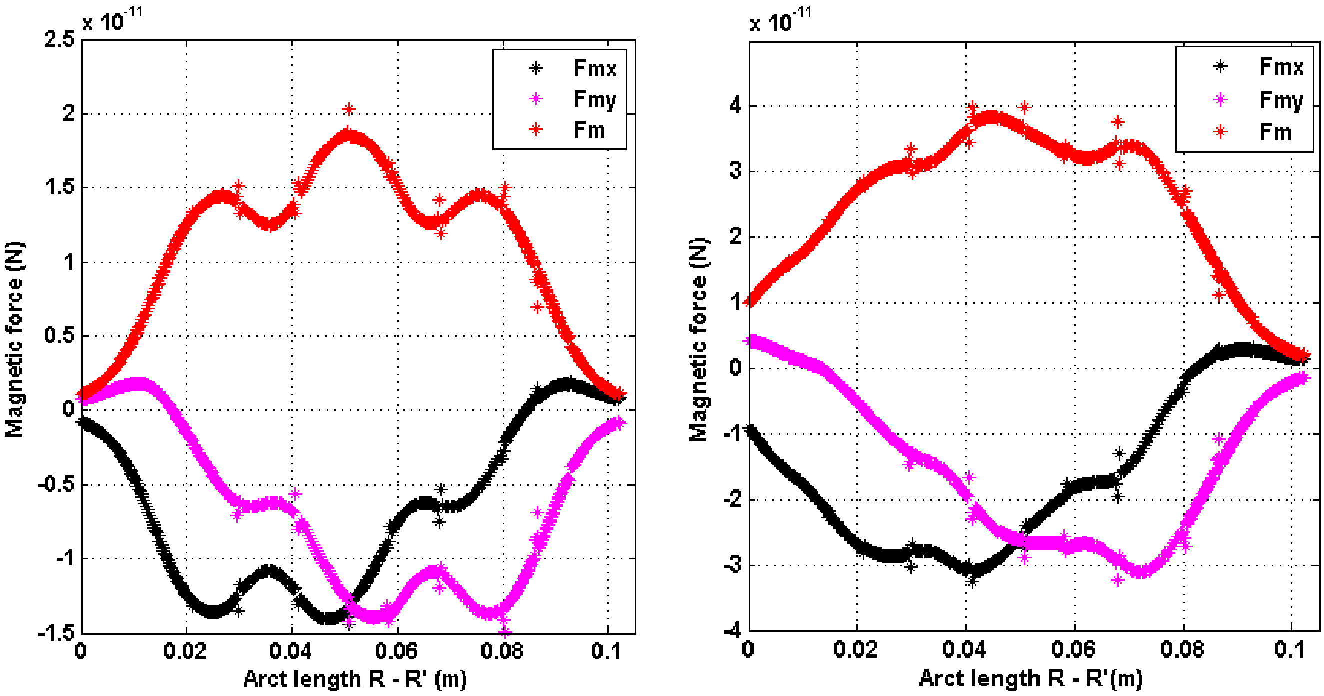
3.3 Particle trajectories

In order to judge the performance and efficiency of the drum separator designed with the Halbach array configuration, we computed and presented in Fig. 7 the



(a) (b)

Fig. 5 Distribution of the magnetic force density in the capture zone: (a) Conventional three permanent magnets configuration; (b) Halbach array configuration

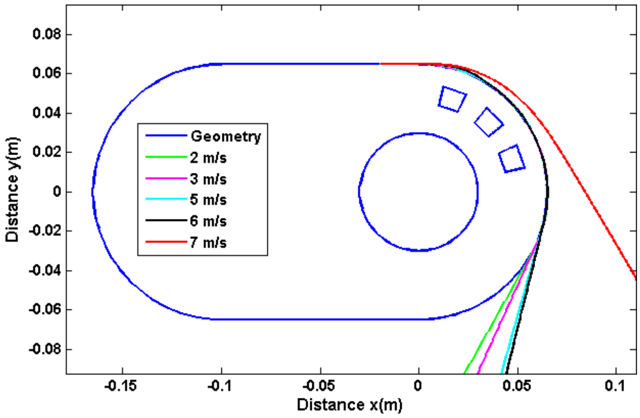


(a) (b)

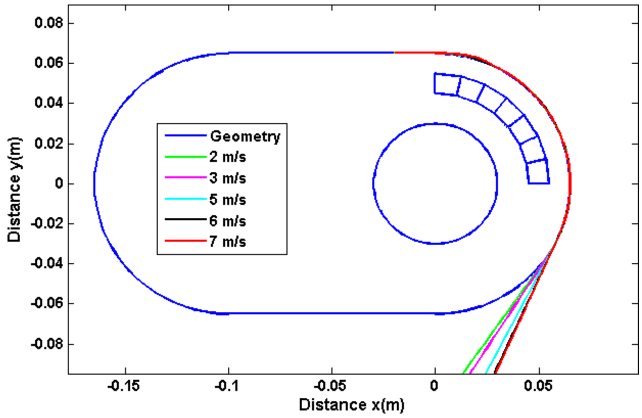
Fig. 6 Variations of the total magnetic force (F_m) and its components F_{mx} and F_{my} in the capture zone along line R–R', results obtained for a cubic iron particle of size 10^{-6} m × 10^{-6} m × 10^{-6} m: (a) conventional three magnets configuration; (b) Halbach array configuration

trajectories of a group of particles transported by the conveyor belt at different speeds.

Fig. 7 shows clearly that the best capture efficiency is obtained by the Halbach array magnets configuration notably for cases of high speeds of the conveyor belt.



(a)



(b)

Fig. 7 Particle trajectories for different belt speeds: (a) Conventional three permanent magnets configuration; (b) Halbach array configuration

4 Conclusion

This work represents a contribution to the design of magnetic drum separators. The use of Halbach array configuration has considerably improved the separation efficiency of fine iron particle especially for high speeds of the conveyor belt. In the achieved simulation, only magnetic and gravitational forces were considered. The 2D resolution of the separation problem is justified by the need to computational cost minimization, the fine size of the particles and their low concentration in the treated material. This study may be a base to a future complete work in which all important separator operating constraints will be taken into account.

Acknowledgement

This research was supported by the DGRSDT of Algeria. The author would like to express their sincere gratitude to the LEC Laboratory of Constantine at Mentouri brothers University Constantine 1 for providing the necessary facilities and equipment. Special thanks are also extended to the Electrical engineering department at the University 20 august 1955 in Skikda for the grants we received.

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