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Experiment realization and simulation of new vertical rotating disk of eddy current separator

***Abstract**. The eddy current separation is an efficient and simple technique to recover conducting particles without contact and doesn't need water in the separation process. There are several types of eddy current separators in industry that can be classified according to different characteristics: kind of separates particles, orientation: horizontal and vertical, magnetic field magnitude: high gradient and intensities, and other criteria. The aim of this paper is to concept eddy current separator prototype of rotational vertical disc with a new improved concept of strong permanent magnet distributions of 8 poles. This kind of separator uses spiral or big permanent magnets with few numbers, but our devise is characterized by an important number of strong permanent magnets on the surface of vertical disk to produce an important magnetic field and strong ejection force. The eddy current separator is modeled and simulated with finite element method to show the magnetic flux density near the dynamic separator and to compute the induced current and Lorentz force on two different natures of non-ferrous particles. The experiments separation results by this new prototype help to recovery non-ferrous particles from mixture waste using ejection magnetic force with a rate of 100%. Moreover, the device was developed to sort and purify the non-ferrous particles with maximum separation rate and important ejection distance. The proposed simulation and experiment results can be used to improve several separator parameters.*

***Streszczenie.** Separacja prądami wirowymi jest wydajną i prostą techniką odzyskiwania cząstek przewodzących bez kontaktu i nie wymaga wody w procesie separacji. W przemyśle istnieje kilka typów separatorów wiroprądowych, które można sklasyfikować według różnych cech: rodzaj oddzielanych cząstek, orientacja: pozioma i pionowa, wielkość pola magnetycznego: wysoki gradient i intensywności oraz inne kryteria. Celem artykułu jest koncepcja prototypu separatora wiroprądowego z obrotowym dyskiem pionowym, z nową, ulepszoną koncepcją rozkładu silnych magnesów trwałych o 8 biegunach. Ten rodzaj separatora wykorzystuje spiralne lub duże magnesy trwałe o niewielkiej liczbie, ale nasze urządzenie charakteryzuje się dużą liczbą silnych magnesów trwałych na powierzchni pionowego dysku, aby wytworzyć ważne pole magnetyczne i dużą siłę wyrzutu. Separator wiroprądowy modeluje się i symuluje metodą elementów skończonych, aby pokazać gęstość strumienia magnetycznego w pobliżu separatora dynamicznego oraz obliczyć indukowany prąd i siłę Lorentza na cząstkach metali nieżelaznych o dwóch różnych naturach. Wyniki eksperymentów separacji prowadzonych za pomocą tego nowego prototypu pomagają odzyskiwać cząstki nieżelazne z odpadów mieszaniny przy użyciu wyrzucającej siły magnetycznej ze 100% szybkością. Ponadto opracowano urządzenie do sortowania i oczyszczania cząstek metali nieżelaznych z maksymalną szybkością separacji i istotną odległością wyrzutu. Zaproponowane wyniki symulacji i eksperymentów można wykorzystać do poprawy kilku parametrów separatora. (**Realizacja eksperymentu i symulacja nowej pionowej tarczy obrotowej separatora wiroprądowego**)*

Keywords: Disk, Eddy currents, Permanent magnet, Separator, Vertical.
Słowa kluczowe: Dysk, prądy wirowe, magnes trwały, separator, pionowy.

Introduction

Eddy current separation is extensively used in different scientific applications as it has attractive features like an acceptable rate of separation and high efficiency, it doesn't need contact and water to sorting the non-ferrous particles from waste, and different sizes and kind of particles nature [1-5]. The better performance of the eddy current separator offers high efficiency in terms: magnetic ejection force of non-ferrous particles, better sorting, and recovery of copper has attracted much attention. Due to this simplicity is popularly used in typical applications like: recovery, chemical, biological and water purification etc [2]. Performance enhancement of magnetic separators is highly indispensable, particularly in small particles size applications like mining and nuclear plants [2].

The eddy current separation process development in design (orientation, static or dynamic, form, speed, and number of permanent magnets) has been the key factor in improving the separation rate from several waste types as a function of particles size and nature [6-10]. The eddy current separators can be categorized according to different criteria, including Magnetic field strength, material, Operating principle, and application domains [2]. Several eddy current separators have been developed with different structures: skewing, vertical and horizontal drum, nature of magnets or electromagnets, variation of pole, superconducting coil, etc [1]. As time progresses, the traditional vertical drum configuration will be gradually replaced by a vertically arranged disks or plates. Because the vertical disk eddy current separator presents numerous advantages in comparison to conventional drum separators: easy and precise simplified design to control the separation process, less expensive (cost, a reduced number of permanent magnets, and a less complex construction), better rate of recovery separation with higher purity, and the separator take limited space-efficient [11,12]. The most scientific and experiment paper study eddy current separators with rotate drum, either in simulation or experiment separation [5,7,8]. But a few papers are interested in the disk separator because the less rate of separation. The vertical disk eddy current separator is developed by eddy current technology in the late 19th century. The first application of vertical disk uses the big permanent magnet with few number [2]. The disk separator has spiral shape made of permanent magnets. It has undergone a numerical simulation to demonstrate the significant distance between magnets (the air gap and working area) required to generate a substantial force [13]. Several research patents increasing the effective area of permanent magnet, flow rate of the material, magnetomotive force, added the conveyor belt, angular velocity, magnetic field strength, and distance ejection. The separation results of non-ferrous particles are considerably improved [14,15]. A new variation of the eddy-current separator called the single disk eddy-current separator (SDECS) has been created. This innovative design features an inclined horizontal rotary disk that is coated with permanent magnets [16].

For this reason, our study focuses on improving the disk separator design and performance (in structure, number, shape, and nature of a permanent magnet) by modeled and simulated the vertical disk of permanent magnets by numerical and dynamic study and experiment prototype. The aim of this paper is to study and analysis, a new improved concept of strong eddy current separator by finite element method. The magnetic performance and characteristics of the separator are computed with numerical modelling and simulation of rotating vertical disk with a new concept of a strong and important number of permanent magnets. The Eddy current separator can be improved through new design reform and technique changes.

The modeling and simulation aims are to show:

- Magnetic flux density distribution lines,

-The magnetic interaction between magnetic separator and the nonferrous particles

-Eddy current in the two types of non-ferrous particles

- Repelled force estimation (in transient module and eddy current state).

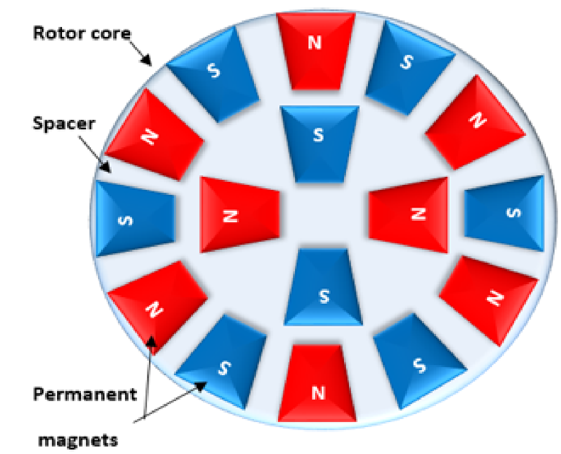
The conception of vertical disk eddy current separator (VDECS) is assured in MAGLEV laboratory of Yildiz university, Istanbul Turkey. The experiments prototype sort and purify two kinds of nonferrous particles (aluminum and copper) using Lorentz force, with an important separation rate and important ejection distance. The combination between simulation and experiment results explains the effect of speed and particles types on separation force and ejection distances; other parameters can be optimized to improve the separator performance.

2. Materials and methods

2.1 Vertical rotational disk eddy current separator application

A 3D view of dynamic vertical disk by an important number of strong permanent magnets around the surface, studied in the present work is shown in Fig. 1. The metallic disk is made from structural steel, and the permanent magnets with the high-quality alloy neodymium (Ndfeb35) with a residual magnetic induction Br= 1 Tesla with high magnetic field in order to generate the very important Lorentz force and big eddy current in particles. The permanent magnetics are fixed with alternating poles polarity N–S and S–N, respectively. The separator is designed with 16 permanent magnets or 8 disk poles.

(a)



(b)

c)

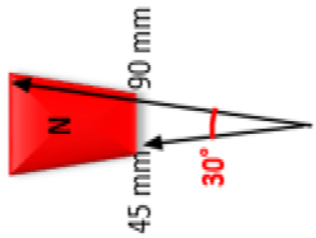


Fig. 1 Rotating vertical disk with permanent magnets Ndfe35 of the designed separator: (a) structural disk with opposite polarity, (b) experiment disk with permanent, (c) geometry and size of on permanent magnet.

2.2 Mathematical model

The process of creating the magnetic model for a rotating separator includes utilizing Maxwell's equations and taking into account the unique properties of permanent magnets [2,6]. To calculate the changing magnetic field generated by a spinning permanent magnet disk, we utilized the transient model with the finite element method, using the mathematical model of modelling to solve the provided equation [2,17,18]:

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

The magnetic flux density $\vec{B}$, the magnetic vector potential $\vec{A}$, magnetic permeability (μ), residual magnetic flux density of the magnets $\vec{B_r}$ at the particle, electrical conductivity particle (σ), and displacement velocity $\vec{v}$.

The magnetic force applied on a magnetic particle is given by:

(2) $$\vec{F_m}=\mu_0\int_{vp}(\vec{M}\cdot\vec{\nabla})\vec{H}dv$$)

Where, $\vec{H}$ represents the magnetic field strength at the particle location, $\vec{M}$ denotes the particle magnetization, $\mu 0$ stands for the magnetic permeability of vacuum, and $\boldsymbol{v}$p represents the particle volume [1,2,11].

The expression that describes the current density generated in the conductive particle due to changes in the applied field can be given by:

(3) $$\vec{J}_F=-\sigma\frac{\partial\vec{A}}{\partial t}$$

The generation of an additional component of the induced currents occurs as a result of the particle's displacement in the applied field is given by [11,12]:

(4) $$\vec{J}_{Fa}=\sigma\left(\vec{v}_p\times\vec{B}\right)$$)

The resulting force exerted on the conductive particle can be expressed as follows:

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

2.3 Model implementation

The establishment of the separator with the pretreatment process begins with geometry generation, insertion of physical properties of each subdomain material (permanent magnets, disk, air, particles, air gap), setting of magnetic alimentation and boundary conditions, magneto dynamic model, and computation step according to time variation, and subsequently extraction of simulation results.

2.4 Mesh Resolution

Fig. 2. shows the finite element model of the vertical separator with triangular element subdivision. The magnetic disk was analyzed by FEM software [19]. In these analyzes, the single disk, the air gap and speed rotation are considered in simulation. The mesh of magnetic drum is shown in Fig. 2.

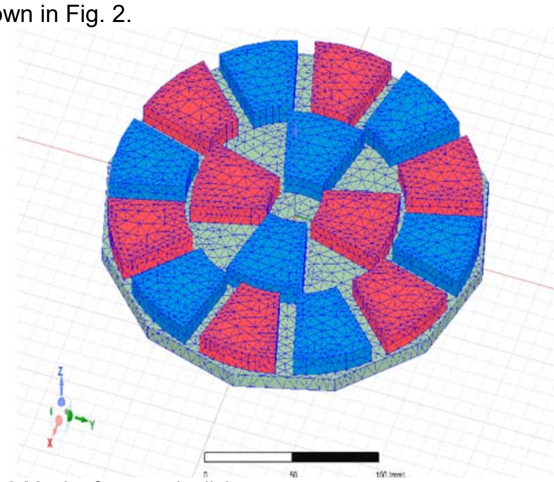


Fig. 2 Mesh of magnetic disk

3D model and numerical simulation are required for accurate magnetic analysis of vertical rotating disk eddy current separator. The 3D Finite Element method (FEM) is used by rotating mesh (moving mesh) gives exact simulation results because of the complex geometric and magnetic nonlinearity. The best refines and mesh resolution give an accurate field solution with convergence criteria. The different parameters such as magnetic, speed, insulation, and the meshing of all parts are assured by tetrahedral elements and, boundary constraints are defined; the domain study of rotating magnetic field is chosen to study the time-varying(fig.2.).

3. Simulation results

3.1 3D Simulation of vertical rotational magnetic disk

Simulation results of rotating disk separator (design of the shape and number n of magnet, pole pairs) with different polarity of permanent magnets are shown in Fig. 3.

The magnetic distribution lines around the device represent the interaction between polarities of permanent magnets, were studied numerically using the finite elements method of numerical software. The aim is to generate accurate real computation results.

Fig. 3. represents the distribution of the magnetic flux density and magnetic field near the magnetic disk in static state. This result shows a high concentration around the permanent magnets placed in a vertical disk; this distribution becomes small proportions moving away from the separator.

a)

b)

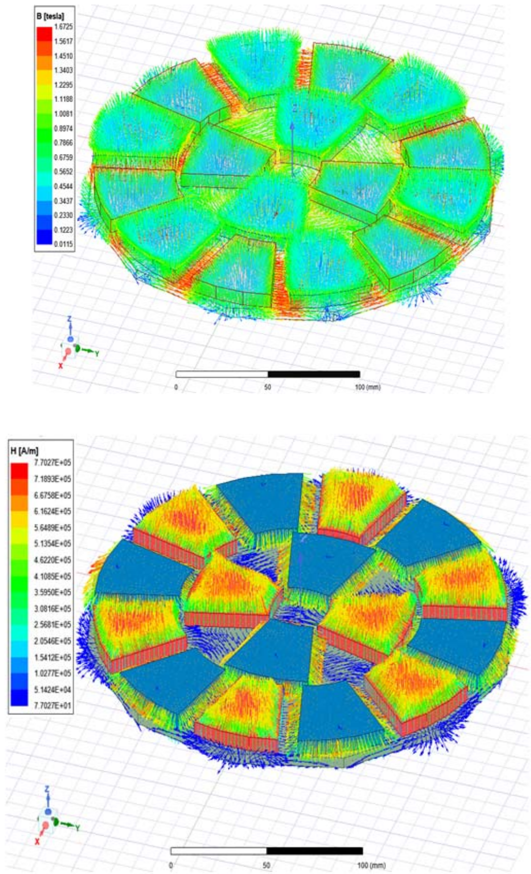


Fig. 3 Magnetic characteristic of separator: (a) Magnetic flux density norm (T), (b)Magnetic field

3.2 Presence of rectangular non-ferrous particles near the separator

The multiplication numbers of permanent magnets result in a significant induced current within the particles, leading to a substantial and swift variation of the magnetic field.

Fig. 4 depicts the eddy current observed in 3D rectangular non-ferrous particles at various rotation speeds during the recovery process by the separator.

As the rotational speed increases, the eddy current in the particles becomes more significant due to the higher frequency of the magnetic field.

The initial alternating magnetic field of the separator induces a second opposing magnetic field in the nonferrous particles. This phenomenon of electromagnetic induction is based on Faraday's law. The variation of magnetic flux induces current in the particles by skin effect.

The numeric simulation of Eddy current in particles is very important because: the distribution of induced current will depend on the different parameters and will affect the strength of Lorentz.

Eddy Current Separation based on Lorentz ejection force produced by interaction between the first magnetic field of permanent magnet disk and magnetized non-ferrous particles by the opposition.

Fig. 5. show, Computation of induced current and ejection force on two types of rectangular non-ferrous particles (Al and Cu) according to speed variation from 300 Rpm to 2400 Rpm.

The Lorentz force exerted on rectangular copper particle is very important than and aluminum particle because the different conductivity ($\sigma_{Cu} > \sigma_{Al}$). This force is important parameters in separation process and she affects directly the rate of separation and purity of sorting.

a)

b)

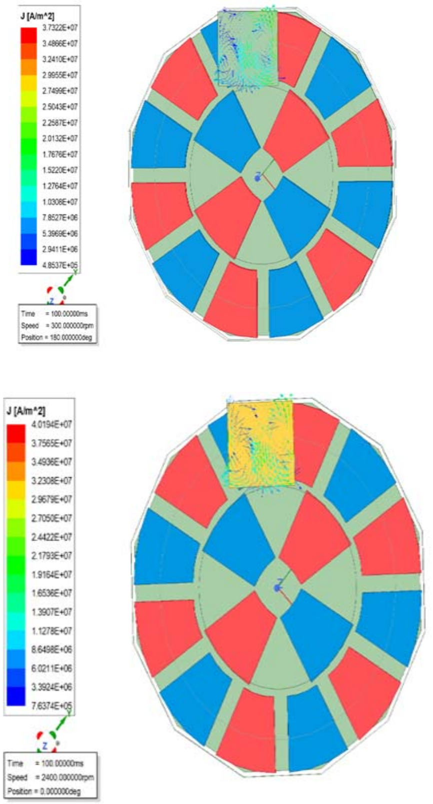


Fig. 4 Eddy current in 3D rectangular copper particle: (a) 300 Rpm, (b) 2400 Rpm

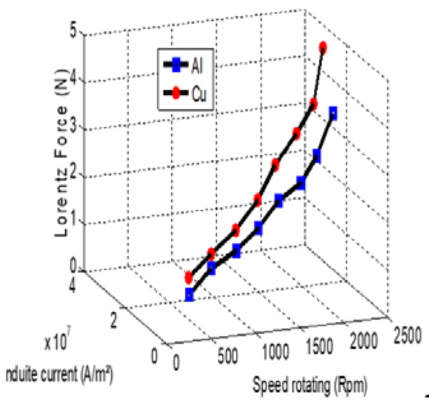


Fig. 5 Induced current and ejection force on two types of rectangular non-ferrous particles

4. Experimental investigation

4.1 Materials

In this section, we present an experimental Realization of separation device, the strong variable magnetic field generated by the rotating vertical disk has 16 poles. Standard Ndfeb35 Axial permanent magnets with 5x10x50 mm dimensions are used, these magnets are placed in steel disk of diameter 25 Cm. The big size of permanent magnets volumes and the number of poles increase the magnetic field around the devises and ejection force.

4.2 Principe of eddy current magnetic separator

The strong variable magnetic field of the rotating disk produces eddy current in the nonferrous particle according to Faraday's Law. The last one generates opposite second magnetic field in the nonferrous particles according to Ampere's Law. The interaction between two magnetic field (primary and second) will produce a repulsion Lorentz force, this force moves and project the particles right or left direction from separator.

The magnetic disk of permanent magnets is the essential part of eddy current separator process, the mixture particle falls near the disk without contact. The experiment setup model is shown in Fig. 6.

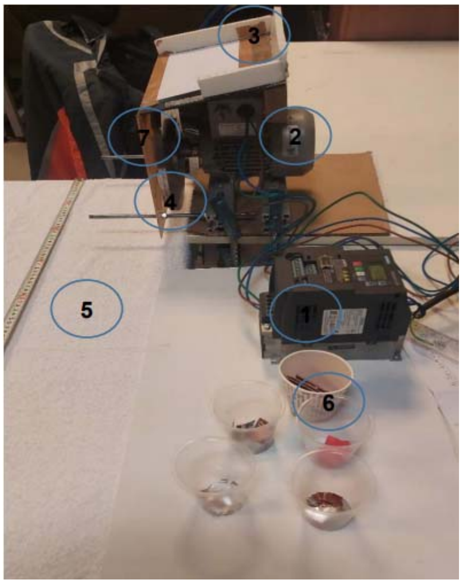


Fig. 6 Setup of magnetic separation device 1-Driving motor command 2-Motor 3-Feeder 4-Permanent magnet disk 5-Collectors of fall particles 6- Particles waste 7-Plastic Isolation

The eddy current separator is dedicated for simultaneous separation of non-ferrous (conductive) particles and consists mainly of a permanent magnet disk placed directly on the axis of an electric engine. The magnetic disk is driven by a variable speed engine through a variable speed drive. In the realized prototype contains a permanent magnet disc alternating NS and SN which generates a significant field gradient. A quantity of particles is injected at the feeder, which they fall (affected by vibration and tilt) and pass near the magnetic disk surface, their ejection trajectory is influenced by the applied field. We have measured the distance between the fall position of the separated particle and the reference line using a graduated ruler (see Fig. 6).

4.3 Experiment results

Separation of big particles waste with same size of: aluminum and copper particles (rectangular form and size of 5x5cm with depth of 2mm) with rotation speed of disk 2400 Rpm.

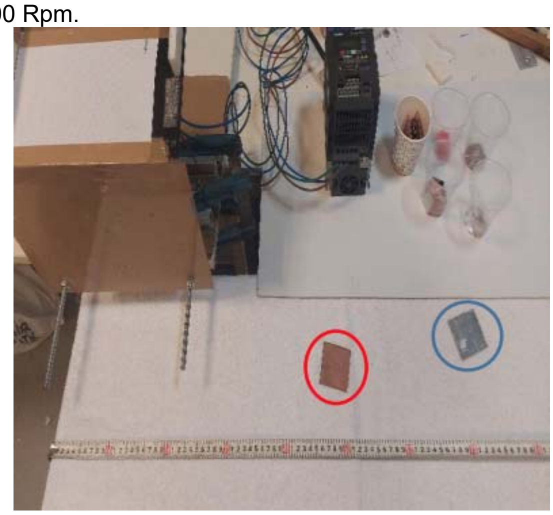


Fig. 7 Ejection distance of non-ferrous particles

The experimental setup for measuring the ejection distance of the two particles nature particles are shown in Fig. 7. The ejection distance for aluminum particle is bigger than copper particle because the different nature and weight of nonferrous particles.

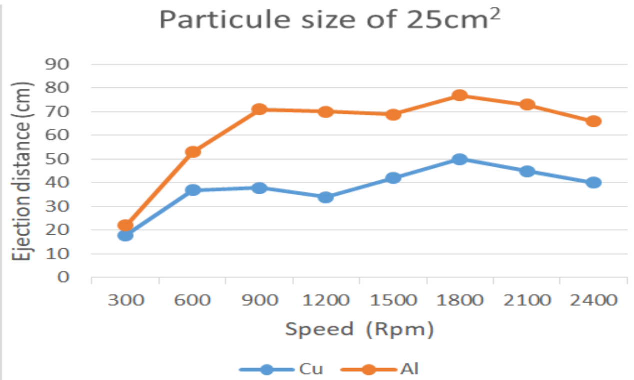


Fig. 8 Ejection distance of non-ferrous particles

The ejection distance of copper change from 18 Cm to 50Cm, but for aluminum vary from 21 to 81Cm according 300 to 2400Rpm respectively. The experiment results show the efficiency of separator to sort the different kind of non-ferrous particles. It can be seen from Fig. 8. that the speed variation of magnetic disk affects directly the ejection distance of particles. Because the waveform and intensities of generated magnetic field change according to speed rotating disk.

The relationship between experimental and simulation results lies in how the simulations elucidate the impact of velocity on the induced current and ejection force. The ejection force, in turn, influences the distance to which particles are ejected during the separation process in the experiment. "In spite of the higher ejection force for copper compared to aluminum, the ejection distance is shorter, which is attributed to the higher weight and gravitational force of copper compared to aluminum (the ρ/σ ratio directly influences the ejection distance).

5. Conclusions

This paper focuses on investigating and analyzing a novel concept involving a vertical disk used in an eddy current separator. The study utilizes a 3D numerical computation model established through the finite element method software. The paper's simulation results highlight the following key aspects:

1. The magnetic field generated around the separator during its operation.
2. How the induced current and Lorentz force change in response to variations in the speed of the disk.
3. A comparison of the induced current values on copper and aluminum particles positioned in the same location.
4. The impact of speed changes of the disk on the force waveform.

The eddy current separator, which is implemented with a vertical disk containing powerful permanent magnets of 1 Tesla and a significant rotating speed, has been successfully realized. The researchers constructed an experimental setup to separate two types of nonferrous particles from waste under different operating conditions, such as variations in particle nature and disk speed. The experimental results demonstrate that increasing the magnetic disk speed from 300 to 2400 Rpm significantly enhances the ejection distance, achieving a remarkable 100% rate of successful separation for the prototype of the separator. In future work, there are plans to utilize the finite element method to simulate and separate small non-ferrous materials using a rotating magnetic disk. The separation objective is to optimize various parameters to achieve efficient separation, Encouraging the adoption of sustainable practices and the preservation of resources.

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