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Simulation of Eddy Current and Repulsive Force of Non-Ferrous Particles in Eddy Current Separator

Abstract*. Eddy-current separation can be an effective technique for sorting non-ferrous metals from nonmetallic wastes. In this paper, we simulate the magnetic characteristics of rotational eddy current separator rounded by drum of permanents magnets in two dimensions, used to sort a mixture of non ferrous particles of different nature. The induced current and magnetic force of ejection in different kind and size of non-ferrous particles are simulated and computed by using the finite element method with Comsol Multiphysics software. The aim of this work is to show the magnetic performance of separator and induced current density in particles, the influence of the conductivity of each of non-ferrous particles on the eddy current and the repulsion force.*

Streszczenie. *W artykule przedstawiono symulację pracy separatora magnetycznego z bębnem złożonym z magnesów i wykorzystującego prądy wirowe. Układ separatora i charakterystyki separowanych elementów modelowane są metodą elementu skończonego z wykorzystaniem oprogramowania Comsol Multiphysics.* ***Symulacja separatora cząstek nie-ferromagnetycznych wykorzystującego prądy wirowe***

Keywords: Eddy Current Separator, Magnetic Field, Repulsive Force, Non ferrous particles.
Słowa kluczowe: separatior magnetyczny, prądy wirowe, Comsol Multiphysics

Introduction

The waste quantities increase, according to time and especially with the technological development. The importance environmental pollution has been generated by electronics scrap refrigerator, television, end-of-life vehicles,… A waste contains different materials, for example: the plastic, aluminum, copper, steel, lead, permanent magnet, and residual toxic materials. Eddy-current separation is a user-friendly and effective technique for the separation of nonferrous metals from wastes. Recovering of non ferrous particles from waste by the eddy current separation will bring renewable resources; this technique has been developed with time in many works [1, 2, 3].

The Lorentz force generated between nonferrous particles and the eddy current separator sort nonferrous from non-metals. The researchers develop several experimental works of separation by eddy-current technique for improving the performance of eddy-current separators and separation as: P. Rem, P. Z. Schlettt and M. Iungu. For optimization of separation, for example, many factors are introduced: increasing the magnetic field intensity of permanent magnet, drum speed, size, shape, nature, the conductivity of the particle, the motion of particle and the trajectory [4, 5, 6].

There are several experimental works and analytical computations on permanent magnet eddy current separation but not much work on numerical simulation because there are two problems of particle translation and drum rotation and others problems. Our aim is to simulate rotational eddy current separator of alternating permanent magnets with the presence of non-ferrous particles of different size and nature (conductivities) in two dimensions with constant angular velocity. The aim of the present work is to compute the magnetic parameters of separator, the variation of repulsive force and eddy current density upon a mixture of conductive particles by the finite element method was presented in this work.

Simulation theory

Eddy current magnetic separator

In our simulation, the eddy current separator consists of a material conveyor characterized by velocity *v* equal to 0.5m/s, where the active part is a fast rotating drum covered with permanent magnets of alternating polarity (Alternately N–S and S–N oriented). They latter are mounted parallel with the drum axis. Their magnetic induction is equal to 0.84T, and the speed of the rotating drum is equal to w_m=300 rpm. Figure 1 represents a conventional horizontal rotating drum.

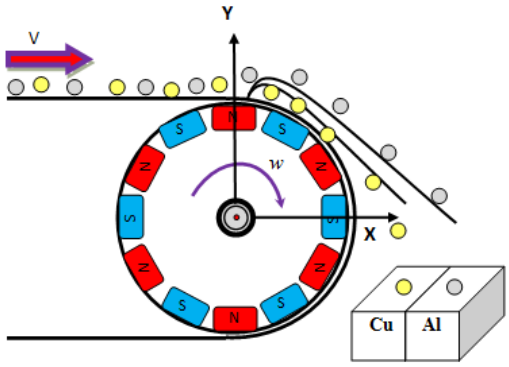


Fig. 1. Rotating eddy current separator

The technology of eddy current separation is based on a physical phenomenon of electromagnetic induction (Faraday's law) and the interaction of repulsive force (Lorentz force) produced by the alternating magnetic field of the drum (created by the permanent magnets) [3,8].

The flow of electrical conductors in an alternating magnetic field induces an eddy current in these conductors. The interaction between these currents and the magnetic field is a repulsive electrodynamics' force on the non-ferrous particles. This interaction separates the non-ferrous particles from non-conducting particles. The repulsive force depends only on the electrical conductivity, permeability of the particles and the alternating value of magnetic flux density [8].

Mathematical model

Alternating magnetic field is produced near the separator by the drum rotation with angular velocity ω_m. The formulations of magnetic flux density profiles can fit a series of expansions in cylindrical coordinates(r, ϕ, z) according to the following formulae [5]:

$$Br=\sum_{n=0}^{\infty} bn\ (r/R)^{-(2n+1)k-1}\sin(2n+1)k(\phi-\omega_m t) \quad (1)$$

(2) $$B\phi=\sum_{n=0}^{\infty}-bn\ (r/R)^{-(2n+1)k-1}\cos(2n+1)\,k(\phi-\omega_m t)$$

(3) $$Bz=0$$

where b_n: Fourier coefficient depends on the magnetic flux density and radial distance (r) , *R:* the radius of magnetic drum [5].

In our work, the electromagnetic problem is solved by Maxwell's equations relating the fundamental electromagnetic quantities. The finite element method (FEM) can be used for the resolution of these equations with the help of COMSOL software [7].

All values of the coefficients must satisfy Maxwell's equation of magnetic conservation :

(4) $$\nabla\cdot\vec{\boldsymbol{B}}=0$$

Which can further be expressed in terms of a vector potential *A* [3]:

(5) $$\boldsymbol{B}=\nabla\times\boldsymbol{A}$$

According to Faraday's law, eddy currents are induced in a conducting particle surrounded by a magnetic field varying with time. The law is one of Maxwell's equations which can be written as follows [3]:

(6) $$\nabla\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial\boldsymbol{t}}$$

On the basis of Ohm's law the induction current is expressed as:

(7) $$\boldsymbol{J}=\sigma\boldsymbol{E}$$

In which *J* is eddy current density and σ the electrical conductivity of the particle [5]. Hence, we obtain the following equation:

(8) $$\nabla\times\mathrm{J}=-\sigma\frac{\partial B}{\partial t}$$

Magnetic fields theory

In this approach, we start with Maxwell's Equations to obtain the magneto-static equation; using Ampere's law [3, 8]:

(9) $$\nabla\times\boldsymbol{H}=\boldsymbol{J}$$

where **H** is the magnetic field.

The solution obtained with FEM allows evaluating the distributions of magnetic field around the drum of the separator [10].

The induced current (J) in circular aluminum particles can be calculated by:

(10) $$\boldsymbol{J}=-\sigma\left(\frac{\partial\boldsymbol{A}}{\partial\boldsymbol{t}}+\nabla\varphi\right)$$

where φ is a scalar potential. It can be determined by the physical conditions under which the eddy currents are induced [10]. It can be established that the scalar potential φ satisfies the Laplace equation:

(11) $$\nabla^2\varphi=0$$

The solution of Eq. (11) for φ can be obtained by the boundary condition. The interaction between the magnetic induction and eddy currents in the non-ferrous particles with a volume V generates a deflecting force F expressed by [3,11]:

(12) $$\boldsymbol{F}=\iiint_V \boldsymbol{J}\times\boldsymbol{B}\mathrm{d}V$$

This equation is used to calculate the force between the particle and magnetic drum.

Where, the physical properties are, the conductivity σ (S/m), angular velocity of the magnetic drum ω_m (rad/s) and the feeding belt speed of the particles *v* (m/s).

This separation force via eddy current in the material is caused by the variable magnetic field of cylindrical drum and is as follows [1, 3]:

(13) $$\mathrm{F}=\boldsymbol{H}^2\frac{\mathrm{np}}{2}\times\frac{\mathrm{m}\sigma}{\rho s}$$

where n number of magnets, p number of pairs of magnetic poles, m mass of particle , σ the electrical conductivity of the particle, ρ the mass density of the particle and s is shape factor of non ferrous particles.

The calculation of the magnetic force acting upon a metal particle depends on several operational parameters for example: ratio of conductivity/density is shown in Table.1, speed of drum, magnetization of permanent magnet and angular frequency of produced alternating magnetic field.

Table.1: Density and conductivity ratio of material.

	Conductivity σ(10^{-8} /Ωm)	density ρ (10^3 Kg/m^3)	σ/ρ (10^3m²/ /ΩKg)
Aluminum(Al)	0.35	2.7	13.0
Copper (Cu)	0.59	8.9	6.7
Silver(Ag)	0.63	10.5	6.0
Zinc (Zn)	0.17	7.1	2.4
Gold (Au)	0.44	19.4	2.26
Lead (Pb)	0.05	11.3	0.4

Results and Discussion

Simulation using the finite elements method

The simulation results of magnetic parameters were studied numerically using the finite elements method with the COMSOL Multiphysics software. The separator drum meshing with smalls particles are shown in Fig.2 and it consists of four pole pairs [1,9].

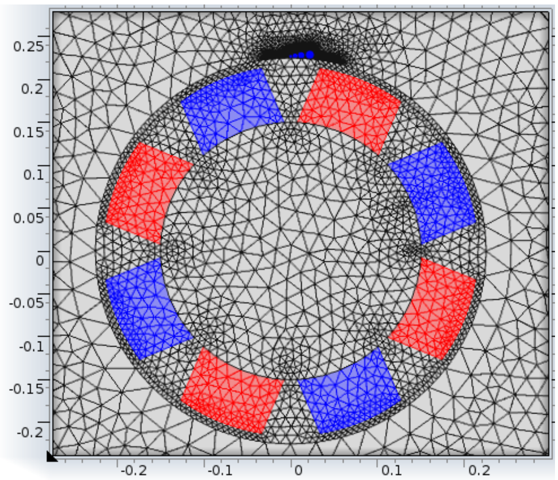
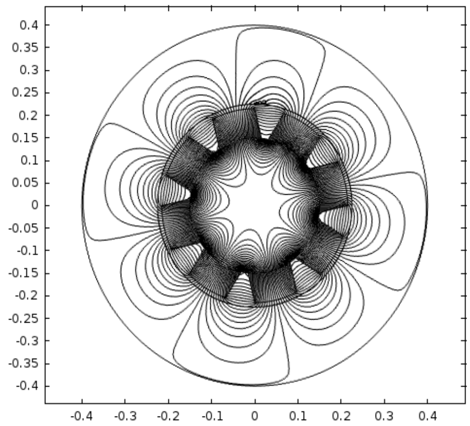
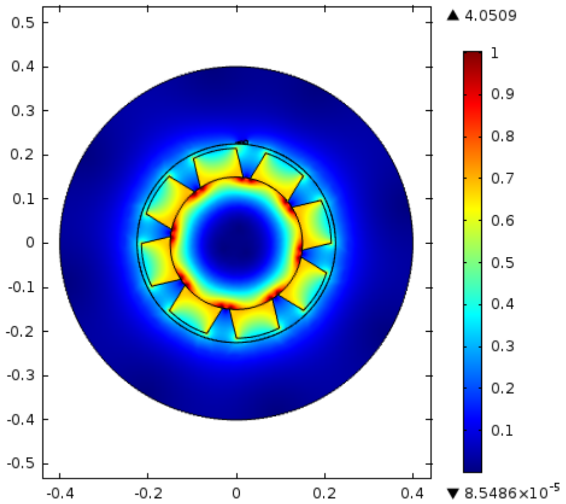


Fig. 2.. Meshing of separator with permanent magnets and particles.

We simulated our permanent magnets to visualize the field lines produced. Simulation results by the COMSOL software of the drum with permanents magnets of different polarity are shown in Fig.3.



a- Magnetic vector potential A produced around (Wb/m)



b- Magnetic flux density (T)

Fig. 3. Magnetic characteristics of the eddy current separator:.

Eddy Current Separation technology principle is based on Lorentz repulsive force (fig. 4) generated by interaction between permanent magnet of drum and non-ferrous particles opposite magnetization of first field, the repulsive force is different because the electrical conductivity of the non ferrous metal, and size, the ejections distance of particles is different.

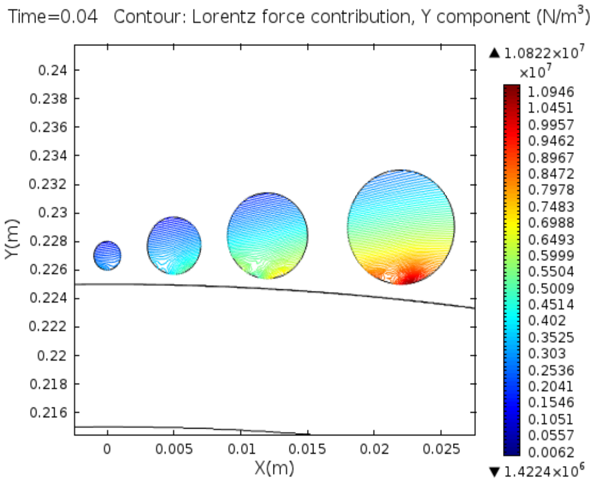


Fig. 4. Lorentz force orientation in conductive particle

Eddy current in non-ferrous particles

The initial alternating magnetic field of the separator induces a second opposing magnetic field in the non-ferrous 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 size and volume and will affect the strength of Lorentz. Fig. 5 shows eddy current in 2D circular non ferrous particles for different radii R equal to 1, 2, 3, and 4 mm) recovered by the separator. When the particle size increases the eddy current in the particles will be very important because the surface of non ferrous particles increase.

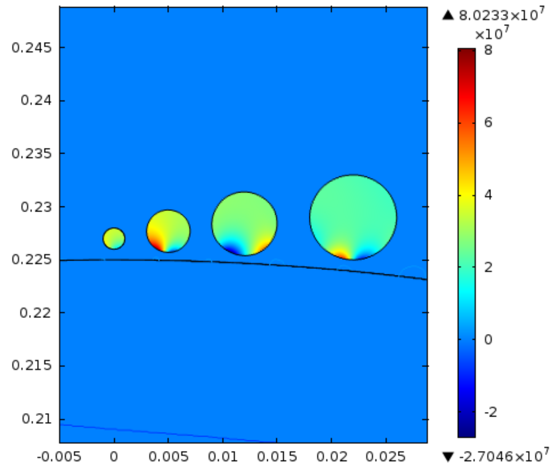


Fig. 5. Eddy current in Aluminum particles

Computation of eddy currents and magnetic force as function of particle size

It consists of computing the maximum values of induced EC and magnetic force with the particles size varying from 1 mm to 6mm at constant drum angular speed of 300 rpm. The results are shown in Table 2 for five elements namely Al, Cu, Ag, Pb and Au.

Table.2: Variation of eddy current with particles size for different elements.

		Radius (mm)					
	Particles	1	2	3	4	5	6
Eddy current (A/mm^2)	Aluminum	40	50	52	55	58	62
	Copper	60	68	73	90	98	105
	Silver	80	90	98	100	108	119
	Lead	4	4.6	5	6	8	9
	Gold	45	60	65	70	78	83
	Zinc	17	19	22	27	34	39

The numeric results show the variation of EC and force with particles size. It is clear that both the EC and force increase with size for different elements (Al, Cu, Ag, Pb, Au and Zn). We can look at this behavior as the variation of EC and force with the electrical conductivity σ for different size (or volume) and table 2.

The particle size directly influences the Lorentz force because the induced current in a large particle (large area) will be big and will give a significant repulsive force between the two poles the particle and the separator see the Fig.6. But the projection distance will respond to the Lorentz force and the force of gravity (the mass density and the weight of small particles) for this reason the non ferrous particles will fall in different positions.

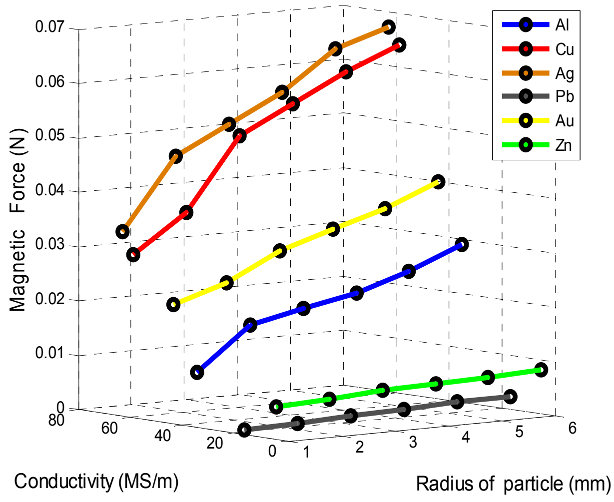


Fig. 6. Repulsive force of different kind of particles

Conclusion

The numerical simulate results show the magnetic characteristics surrounding eddy current separator of permanent magnets in two dimensions (ECS), the eddy current density in non ferrous particles of different sizes. The magnetic force of ejection in different kind of non-ferrous particles are simulated and computed by using the finite element method with Comsol Multiphysics software. When the conductivity and size (surface) of the conductive particles increases the eddy current and the magnetic ejection force becomes very important. Finally, other parameters involved in the simulation ECS could be studied such as: particles shape, the number of permanent magnets of the drum, magnet type and others. These would require more computational time and certainly improve the ECS efficiency.

Nomenclature

α is angle of the particles coordinate in cylindrical system.
b_n Fourier coefficient
B_m Magnetic induction (T)
F Magnetic deflecting force
J Induced eddy current (A/mm^2)
k Sets of symmetric N–S magnets
w_m Speed of the magnetic drum (rad/s),
p number of magnetic poles,
m Mass of particle ,
σ Electrical Conductivity of the particle (S/m),
ρ Mass density of the particle (Ω.m^2)
s Shape factor of non ferrous particles
H Magnetic field
A Magnetic vector potential
Φ Scalar potential
E Electric field
t time
V Volume
R Radius of the drum,
v Feeding belt speed of the particles (m/s)
Al Aluminium
cu Copper
Ag Silver
Pb Lead
Au Gold
Zn Zinc

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