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Faculty of Applied Sciences
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Memory
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Speciality: Electrical machines

Presented **by :**

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theme:

2D simulation and study of the rotational magnetic separator

Submitted to the jury composed of:

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I would like to thank the head of the jury and the examinees for the honor they have given me in agreeing to judge this work.

I also extend my sincere gratitude to my honorable family and all the teachers of the KASDI MERBAH University of Ouargla for their help, support and advice, not to mention all the administrative staff of the department.

Dedicaces

I dedicate this modest work to:

My source of tenderness, the dearest being in the world,

The most patient woman, my dearest mother

, my very dear father and all

their sacrifices

My brothers·

All my family

All the friends

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Chapter II: Mathematical Formulation of Electromagnetic Phenomena

Chapter III: Simulation of vertical eddy current separator

List of symbols

LIMS: low intensity Magnetic Separator

DMS: Dry Magnetic Separator

WDMS: Wet-drum magnetic separators

HIMS: High Intensity Magnetic Separator

LIMS: Low Intensity Magnetic Separator

HGMS: High Gradient Magnetic Separator

ECS: Eddy-current

ECS: Eddy-current separator

σ: Electrical conductivity (10^7 S/m)

ρ: mass density (kg/m3)

LIM: Linear induction motor

VECS: Vertical eddy current separator

DECS: Drum Eddy Current Separation

VDECS: Vertical Drum eddy current separator

HDECS: horizontal drum eddy current separator

IDECS: Inclined Drum Eddy Current Separator

RDS: Rotating disc separators

E: Electric field [*V/m*]

H: Electric field [*A*/*m*]

J: current density[*A*/m^2]

ρ : Volume load [C/m^3]

D: Magnetic induction [C/m^2]

B: Magnetic induction (Tesla)

ε :Permittivity[F/m]

μ :magnetic permeability[H/m]

σ :Conductivity[S/m]

ν = :Magnetic reluctivity [1/ μ]

introduction

General introduction:

The waste volumes in environment rapidly increase, according to time and especially with the new technological development. The importance environmental pollution has been generated by electric device, electronics scrap, end-of-life equipments [1].

A waste contains different materials: non-metallic, metallic, ferrous and non-ferrous, magnetic separation is a user-friendly and effective technique for the separation of 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 [2].

There are several experimental and theory works of computations on magnetic separation but not much work on numerical simulation because the many problems of particle translation and drum rotation and others problems complex geometry nonlinear parameters.

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 and three dimensions with constant angular velocity.

The aim of the present work is to characterize the magnetic performances and parameters of separator, the magnetic flux density, induced current, and repulsive force upon a mixture of conductive particle by the finite element method was presented in this work.

In this work, the Finite element method (FEM) is used for electromagnetic study of new vertical disk of eddy current separator by numerical simulation. The memory contains three chapters:

The first Chapter: includes basic definitions, forms and constitution of different magnetic separators, including the various kind and principle of systems are described.

The second chapter: contains basic concepts about electromagnetic fields, methods of calculating them, and how to model and simulate the magnetic separator.

The third chapter: includes highlighting the simulation results obtained in 2Dimension and 3dimensions , analyzing, computing and measuring of magnetic parameters force and induced current.

Chapter I

Different kind of magnetic separator

I-1. Introduction:

The great amount of industrial and municipal waste has increased significantly in last year's caused by competition and new industrial technology of electronic of Printed circuit board (PCB) card (from electrical and electronic devices) composed by nonmetallic, ferrous, and non-ferrous materials essentially. There are several techniques to sorting and recycling the materials each one has advantage and inconvenient. In Algeria, the amount of household and industrial waste reached millions of tons, however, this waste is not recycled well, and Algeria's waste recycling rate is only 10 percent. This mineral waste has a great economic value if it is recycled. For example, the electronic waste has a lot of mineral like gold, iron aluminum, copper, one of the best solutions to treat this waste is the method of electromagnetic separation, to preserve the environment by recovering the materials from waste. Magnetic separators have been used for many years to recover ferrous and non-ferrous metal from mixture scrap [3].

I-2. Different types of materials:

Household and industrial wastes are both recovered contain: Steel ferrous metals, non-ferrous metals (aluminum, copper), and non-conductive materials are the most commonly recovered materials in industry (plastic and glass ...). Generally, each recycling technique is dedicated to a specific type of waste that has to be recovered.

I-2-1. A Steel ferrous metals:

Recovery and recycling of ferrous metals provide significant revenue in industrial countries; 70 percent of steel from end-of-life products is recovered. Iron is present in ferrous metals, which are magnetic. Steel has the benefit of being magnetic, allowing it to be easily attracted by magnetization. This fundamental property(magnetism), used for their separation from stock of waste, allows it to be recovered even if it is not sorted at source and regardless of the method of treatment of this waste [2,4].

Figure I.1. Ferrous metals.

I-2-2. Non-ferrous metals:

Non-ferrous metals, such as aluminum, brass, copper, and titanium, are metals that do not contain iron. Non-ferrous metals can also be found in alloys, such as brass, which is made up of copper and zinc. It is a metal with interesting physical features that have made it popular in a variety of applications: the most well-known are its lightness and stainlessness, strength, electrical conductivity, and ease of shaping [4]. Eddy-current separation is used to separate non-ferrous metals.

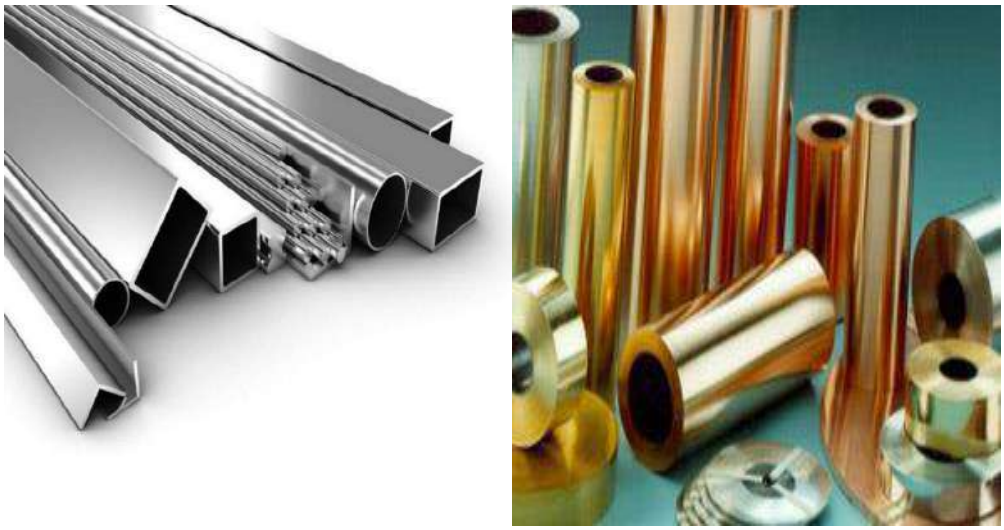


Figure I.2. Non-ferrous metals (aluminum, copper).

I-2-3. Insulating Materials:

They're materials that don't allow electricity to flow through them. These materials are used in electrical appliance parts to support or separate electrical conductors without allowing electricity to pass through. Glass, paper, and Teflon, for example, are excellent insulators.

I-2-3-1. Glass:

Glass is made from either virgin mineral matter (silica) or crushed recycled glass. The amount of glass collected accounts for more than 12% of all household garbage.

I-2-3-2. Plastic:

This garbage represents a significant quantity of recovery, accounting for over 20% of the volume and 11% of the weight of domestic waste recovered each year. Plastic's superior properties (lightness, malleability, impermeability, stiffness, flammability, modularity, and excellent property/cost ratio) make it ideal for waste recovery and treatment.

I-3. Magnetic separation:

Magnetic separation is an old method of sorting iron from nonmetallic other metals waste and concentrating iron ores using magnetic separator, since 1849. The magnetic separator is consisting mainly of a source of magnetic field (permanent magnet, electromagnet or superconducting coil) [2]. Magnetic Separation is the processes to separating based differences magnetic properties of various minerals present in the ore particles [6,5].

I-4. Magnetic separation application:

Magnetic separation is primarily used for two purposes: the purification of wastes of magnetic components and the concentration and separation of magnetic materials [5].

In many areas of life, such as industry, agriculture, water purification, medicine and the environment, and pharmaceutical and biochemical operations, magnetic separation is an efficient and frequently cost-saving technology [7].

I-4-1 the Mining:

In the mining industry, magnetic separation is most commonly used to separate "iron ore," or unwanted waste metals, from the rest of the material [8], while exploiting the different magnetic properties (susceptibilities)[2],The ore is often made up of man-made byproducts of the mining operation, such as wires, nuts and bolts, nails, broken bits from hand tools like jack hammers and drills. [9]

I-4-2. Industrial and environmental depollution:

magnetic separation is utilized in a variety of purification processes, including purification of industrial water (metallurgy and steel industry), urban water, waste water, and nuclear power plant cooling. Its principle is to use a magnetic field to separate colloidal particles by creating interaction forces between the particles and the separation device.

I-5. Permanent magnets:

A magnet is an object or material that generates a magnetic field. This magnetic field is invisible, but it is responsible for a magnet's most notable property: a force that attracts or repels other ferromagnetic materials such as iron, steel, nickel, cobalt, and others.

I-5-1. Types of permanent magnets:

Permanent magnets have advanced significantly in recent years. New materials, such as rare earths (Nd-Fe-B, Sm-Co) with excellent magnetic properties, have appeared in their compositions as a result of new technologies. Permanent magnet are divided into three categories :

Figure I.3. permanent magnet.

I-5-1-1. Rare-earth magnets:

Are powerful permanent magnets created from rare-earth element alloys. Rare-earth magnets, which were developed in the 1970s and 1980s, are the strongest permanent magnets available, They're constructed of a neodymium, iron, and boron alloy ($Nd_2Fe_{14}B$), creating substantially stronger magnetic fields than ferrite or alnico magnets. Rare-earth magnets can create magnetic fields of up to 1.2 T, whereas ferrite or ceramic magnets normally produce fields of 0.5 to 1T.

I-5-1-2. Ferrite Magnets:

Ferrites are ferrimagnetic, meaning they can be magnetized or attracted to a magnet, and are created by mixing and burning significant proportions of iron(III) oxide (Fe_2O_3, rust). Most ferrites are not electrically conductive, unlike other ferromagnetic materials, they resist well to temperature, making them suitable in applications such as magnetic cores for transformers to control eddy currents. Ferrites are classified into two groups based on their resistance to demagnetization (magnetic coercivity): Hard ferrites and soft ferrites.

I-5-1-3. Alnico Magnets:

have a very high remanent field, but a very weak coercive field, and is a group of iron alloys that, in addition to iron, contain aluminum (Al), nickel (Ni), and cobalt (Co) (Co). Copper and, on rare occasions, titanium are also included. Permanent magnets are made from Alnico alloys, which are ferromagnetic.

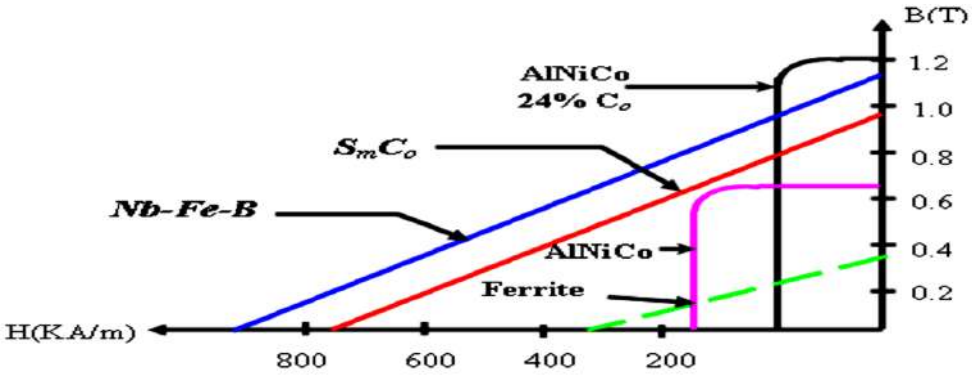


Figure I.4. Curve B (H) of the different types of permanent magnets.

a **b** **c**

Figure I.5. (a) Rare-earth magnets(Neodymium), (b) alnico magnet, (c)Ferrite Magnets

I-5-2. Applications of permanent magnets:

Magnets are most commonly used to create a force that attracts other magnetic components. Permanent magnets and electromagnets are both used in a variety of manufactured items that have a significant impact on our daily lives: **(Motors, machines, Loudspeakers …)**

I-6. Classification of Magnetic Materials:

The magnetic separation is based on the properties of the minerals and on the classification of this one, the magnetic property of minerals of most interest is the magnetic susceptibility(μ), The classification of minerals is:

I-6-1. diamagnetic:

The atoms in a diamagnetic substance have no magnetic moment when there is no applied field. Under the influence of an applied field (H), the spinning electrons precess, and this motion, which is a type of electric current, causes a magnetization (M) in the opposite

direction of the applied field. All materials have a diamagnetic effect. However, another mechanism diminishes the diamagnetic contribution in nondiamagnetic materials. The value of susceptibility is unaffected by temperature. [10] Examples of diamagnetic materials: water ($\chi = -9\times10^{-6}$), copper, graphite, quartz, salt, gypsum, marble, rare gases, diamond and bismuth($\chi=-1.5\times10^{-4}$).

I-6-2. Paramagnetic:

All materials that aren't diamagnetic are paramagnetic. They have a magnetic susceptibility that is positive, almost constant, and very low. Each atom in a paramagnetic substance possesses a non-zero magnetic moment. Among the paramagnetic compounds are air ($\chi = 3.8\times10^{7}$) and oxygen ($\chi = 2\times10^{5}$) as well as aluminum and platinum. [3]

I-6-3. Ferromagnetic:

The Heisenberg model of ferromagnetism is a quantum mechanics model that defines the parallel alignment of magnetic moments in terms of an exchange interaction between neighboring moments. ferromagnetic materials are usually compared in terms of saturation magnetization (magnetization when all domains are aligned) rather than susceptibility [10].

I-7. magnetic separators:

Magnetic separator is a device that separates objects from each other depends on the generation of a magnetic field either by (permanent magnet or electromagnet) Acts selectively with magnetized objects through magnetic force that attracts or pushes this body.

When a body is placed in a magnetic field, the magnetic line may be concentrated inside the body and the body is pushed towards the higher field intensity or the force line maybe expelling from the placed body and as a result the body pushed towards the lower field intensity [6].

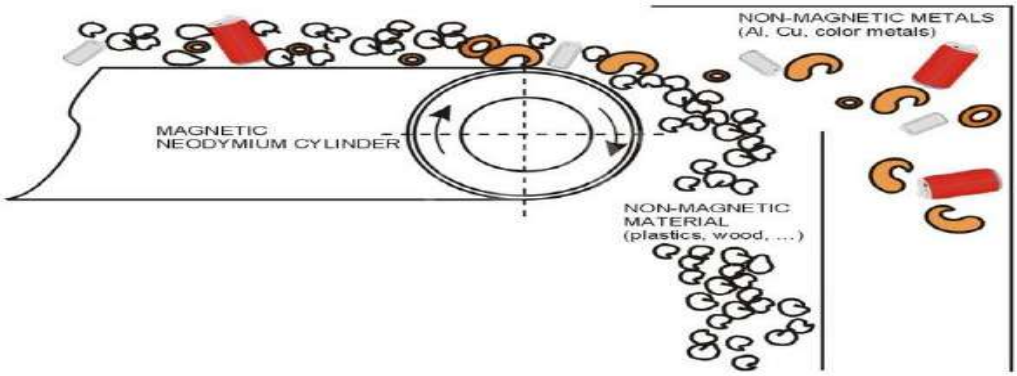


Figure I.6. Magnetic separator.

I-7-1. different type of magnetic separator:

Magnetic separator is divided into two groups based on their nature, magnetic separator wet and magnetic separator dry. But If we get deeper into the characteristics of the components, we can classify the separator into a lot of groups is based intensity magnetic.

I-7-1-1. Low intensity Magnetic Separator:

Low intensity magnetic separators, LIMS, are designed to recover ferromagnetic materials. Their construction is simple with low energy permanent magnet. They are intended mainly for ferromagnetic materials [9]. Low-intensity magnetic separators work in the open field, magnetic lines of force close in a magnetic medium with low permeability like air [2]. Permanent magnet tubes are used to remove very magnetic fine or coarse particles from dry or wet goods, permanent magnet magnetic drum separators are used for continuous and dry treatments of para and ferromagnetic particles [4]. Their magnetic force density ranging from $2*10^4$ to 10^6 N/m^3.

Figure I.7. Permanent magnet magnetic tube (ferrites, rare earths) [4].

I-7-1-2 Dry magnetic separator:

A dry Magnetic separator (DMS) has some disadvantages compared to the wet separator this separator is based on permanent magnets This separator automatically excluded ferrous organs, large pieces contained in metal waste, household and industrial waste. They are mainly three class:

- Suspended separators;
- Magnetic pulleys;
- Scrap metal drums [2]

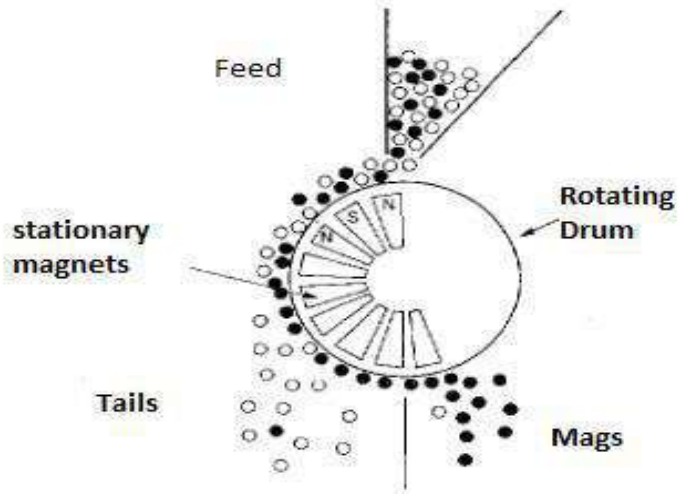


Figure I.8. Diagrammatic illustration of dry drum separator [5].

I-7-1-3 Wet-drum magnetic separators:

Wet-drum magnetic separators (WDMS) are used extensively in the co al industry to recover, for fine particles less than 1 mm, wet separation is utilized. In the iron ore industry, the separators are used to separate the valuable ore from the gangue. And he is best more than the dry magnetic separator.

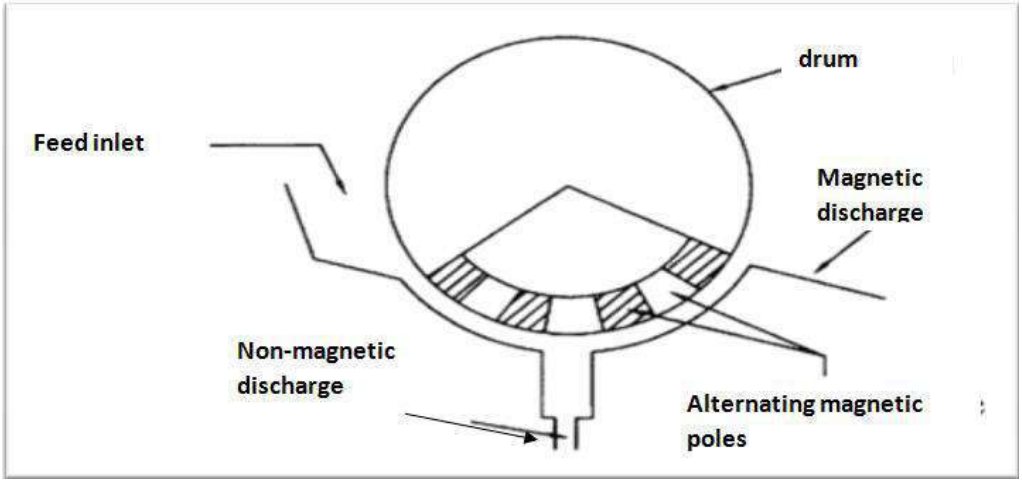


Figure I.9. Schematic of a wet-drum magnetic separator [16]

I-7-1-4 High Intensity Magnetic Separator:

The equipment that creates the magnetic field in a high-intensity magnetic separator is a permanent magnetic or electromagnet. Magnetic separators of this sort are used to separate paramagnetic materials. The density of magnetic force ranges between 2.10^7 and 4.10^9 N/m^3. High-intensity magnetic separators, which can be employed dry or wet, can purify or concentrate non-magnetic materials.

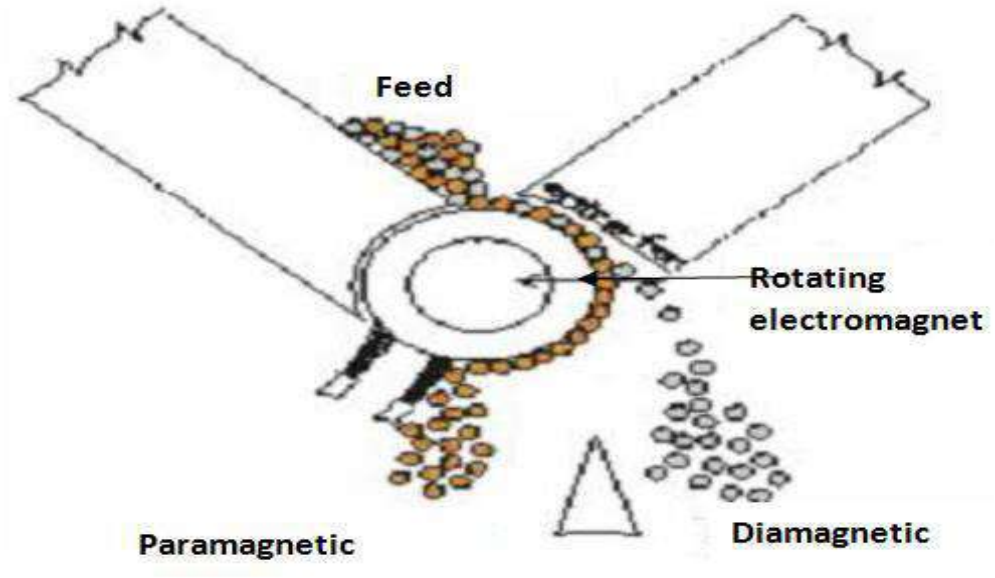


Figure I.10. high intensity Magnetic Separator.

I-7-1-5 High Gradient Magnetic Separator (HGMS):

High gradient magnetic separator (HGMS) is a new type of high intensity magnetic separator developed on the basis of ordinary high intensity magnetic separator [9]. The high magnetic field is produced by the use of superconducting coils made of superconducting alloy which makes it possible to generate a magnetic force density of 6×10^{10} to 10^{12} N/m^3] the (HGMS) makes possible the efficient separation of very weakly magnetic particles of micron size for which magnetic separator are ineffective. [11] One of the advantages of high gradient magnetic interval is the possibility of attracting weak magnetic particles.

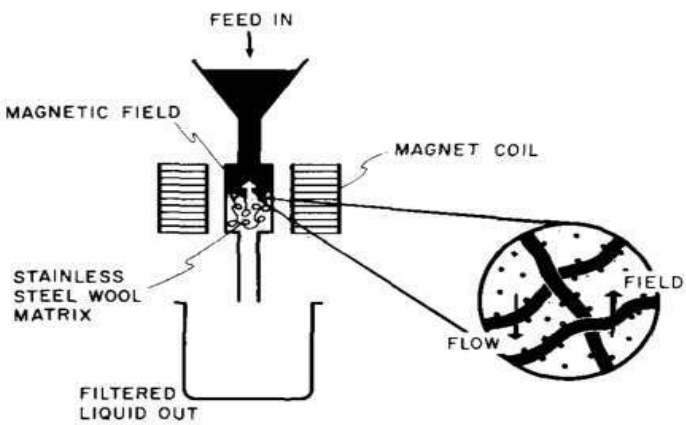
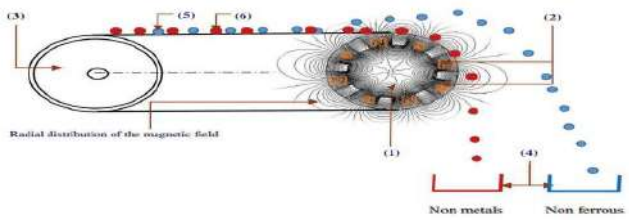


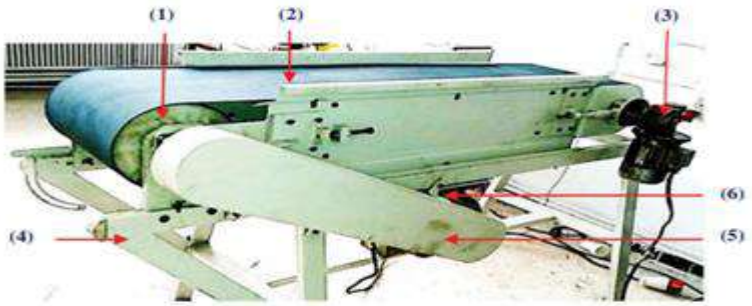
Figure I.11. Schematic high gradient magnetic separator [11].

I-8. Eddy-current separator:

the eddy current separator (ECS) it is a machine for sorting non-ferrous metal waste (aluminum, zinc, copper…) from the waste ferromagnetic (iron) this separator is based on the eddy current. The rotary drum is the most common form of eddy current separator (ECS) currently in use [4]. The eddy-current separator can use permanent magnets, or they can use electromagnets. In eddy-current separators, the eddy currents are induced in the nonferrous metallic particles due to the changing magnetic field in the active zone of the separator. The interaction between these currents and the magnetic field results into repulsive electrodynamics forces on the metallic particles and so into their separation from nonconductive ones, or from each other [13].



FigureI.12. Principle of eddy current separation. 1-Fast rotating drum, 2-Magnets 3- Conveyor belt 4- Collector, 5-non-ferrous particles 6- non-metal particles [4].



FigureI.13. Photograph of the magnetic induction separator: 1-Permanent magnet drum, 2-Antistatic conveyor belt 3-motor gearbox 4-metal frame, 5-belt 6- three-phase high-speed motor; 7-recovery header [4].

I-8-1 Principle of eddy-current separation:

Eddy currents (EC) work by exploiting electric currents produced by a changing magnetic field to generate repulsive magnetic fields for non-ferrous metals. Non-ferrous metals are ejected as a result of these repulsive forces. The "ejected" fraction of non-ferrous metals (often aluminum, but also copper, lead, and brass) and the fraction of other materials that fall at the conveyor's end (ferrous metals, paper, cardboard, plastics, glass, and so on) are directed to two separate recovery devices; this separation can be aided by the use of a dividing plate that prevents the two fractions from mixing [4].

I-8-2 Various Types of Eddy Current Separators:

Nonferrous metals are separated and recovered from home and industrial waste using eddy current separation. Eddy currents are created by an induced voltage in a conductive metal.

Eddy current separation is based on the formation of a moving electromagnetic field flux that causes a repulsive force to be formed in the conductors (non-ferrous metals), repelling them through the opposite field. Weight, shape, material, and other factors influence the repelling force.

There are many methods for creating eddy currents in materials:

- Physical movement of the material to be separated through a magnetic field.
- Movement of the magnet through the material to be separated.
- Temporary change in magnetic field strength in the material to be separated.

The ejection force depends on the generation of eddy currents induced in the particle surface depending on particle size that can be separated.

The ratio (conductivity/density) is an index that indicates how much the repulsive force will affect a material. Table 1.1 shows the conductivity/density ratios for certain conductive materials.

Metal	Electrical conductivity $\sigma(10^7$ S/m)	mass density ρ(kg/m^3)	The ratio (σ/ρ) (m^2/Ω.kg)
Aluminum	3.5	2.7	13
Copper	5.9	8.9	6.7
Silver	6.3	10.5	6.0
Zinc	1.7	7.1	2.4
Brass	1.4	8.5	1.7

Table III.1. Electrical Conductivity/Mass Density ratio for Various Nonferrous Metals

I-8-2-1. Linear induction motor (LIM)

These are eddy current separators where the source of the field used is very much like the stator of a three phase motor except the motor has been opened up and flattened. The windings of linear motors are powered by an AC voltage source with a frequency of 400-800 Hz. Linear motors are installed below and above the treadmill. They produce a sinusoidal magnetic field. When the conductive particles pass through the active separation zone (between the LIMs), they are pushed under the effect of the Lorentz force away from the source of the field.

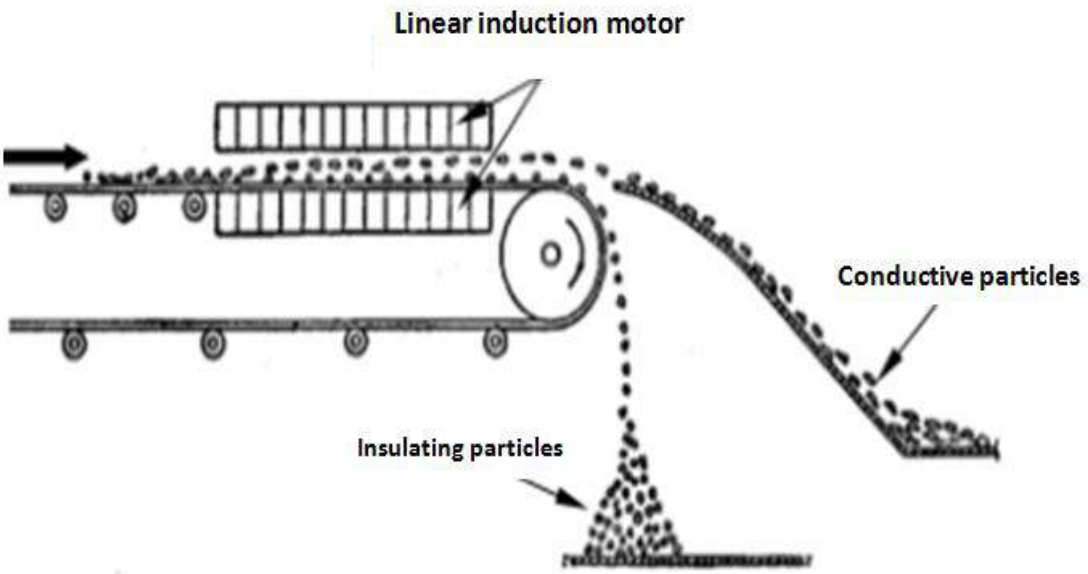
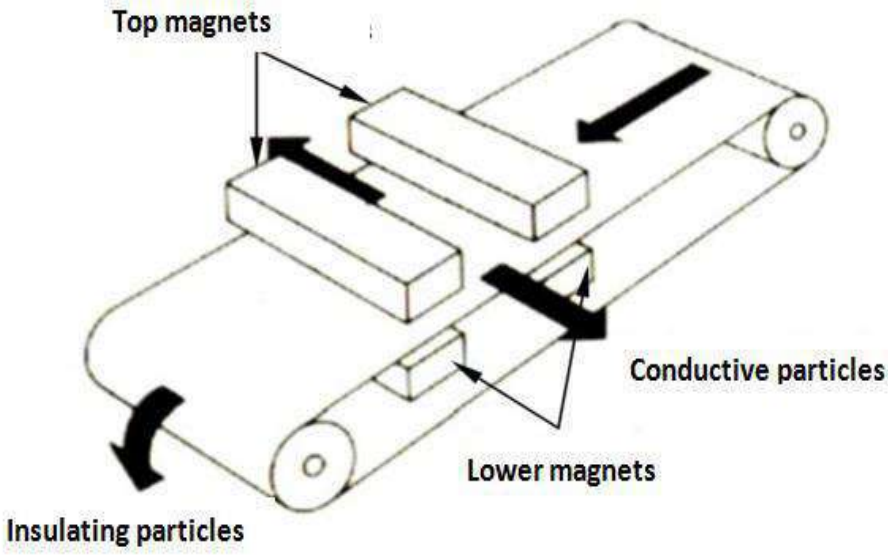


Figure I.14. Magnetic separator based on LIM

I-8-2-2 Dual magnet system

A double magnet system consists of a conveyor with two magnetic assemblies above and below the belt, with an air gap of roughly 3.5 cm between the magnets. The Covered metals are pushed to the edge from the side of the belt when the material passes past the first pair of magnets. The metals are forced to the other side of the belt when they pass over the second pair of magnets. The targeted particles are pushed to the margins of the belt, where they are rejected [2].



FigureI.15. Magnetic separator with Dual magnet system

I-8-2-3. Static separator

a. Inclined Table Separator

The mechanism runs on a stainless steel ramp that is set at a 45-degree angle. The material to be separated will be dumped into the chute above the ramp, which is placed beneath the surface of the ramp, and will be separated by a system of permanent magnets of alternating polarity. The material slides down due to the varying acceleration, making separation easier. Eddy current forces have an effect on the metal particles. These are pushed to the ramp's side. Non-metallic particles are unharmed as they glide down the ramp [2].

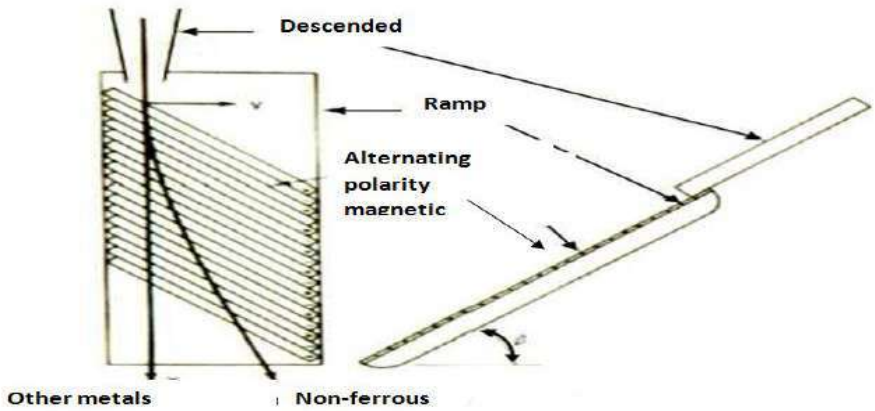


Figure I.16. Inclined Table Separator

b. Vertical eddy current separator

The vertical eddy current separator (VECS) was made up of two vertical steel walls that ran in tandem with the inner walls' magnetic bands of alternating polarity. Conductive particles will be repelled by an inhomogeneous magnetic field, whereas non-magnetic particles would fall victim to gravity. This separator was essentially a hybrid of two separators positioned vertically atop ramps.

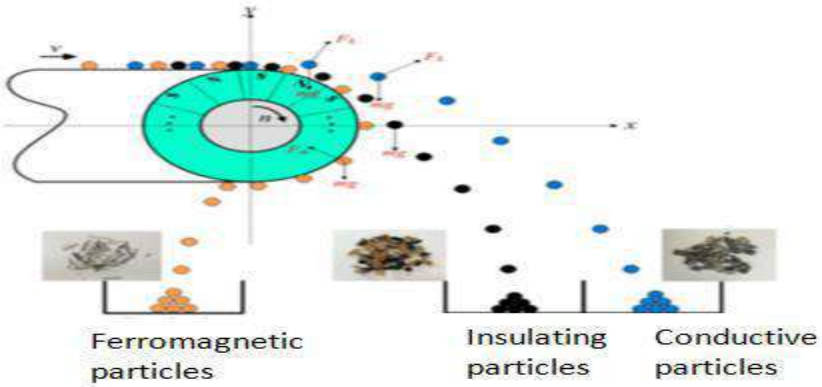
I-8-2-4 Drum Eddy Current Separation

a. Vertical Drum Eddy Current Separator

Vertical drum eddy current separators (VDECS) are originally introduced by the Delft University of Technology, the Netherlands. This type of separator is composed of two parallel vertical walls in mild steel with magnetic strips of alternating polarities. This structure is similar to a combination of two vertically mounted ramp separators. Conductive particles passing through an inhomogeneous magnetic field are deflected while non-magnetic particles fall under the effect of gravity. These dividers can be thought of as a combination of two vertically mounted ramp dividers.

b. Horizontal Drum Eddy Current Separator

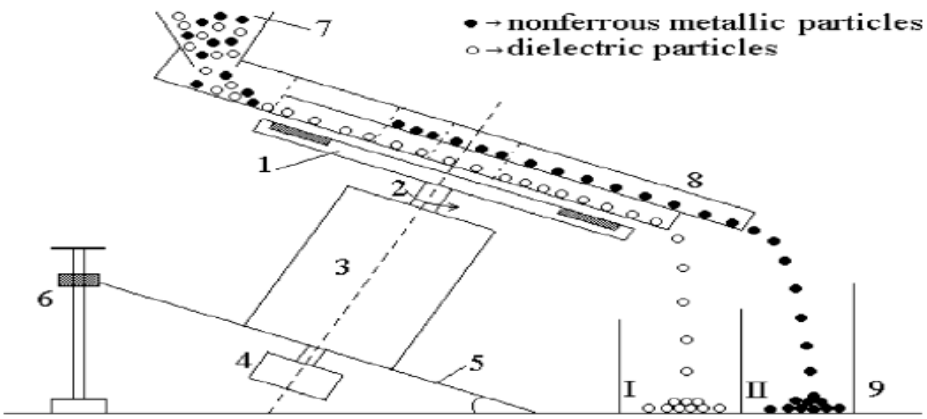
The horizontal drum eddy current separator (HDECS) consists of a cylinder fitted with a succession of permanent magnets of alternating polarity placed at one end of the separator. This rotor rotates at very high speed in order to generate an intense dynamic magnetic field. The feed stream is introduced through a treadmill. When the conductive particles arrive in the vicinity of the magnetic field, they are propelled out of the machine, while the inert materials fall by gravity along the normal path into another collection container. The ferromagnetic particles are attracted by the magnetic field and discharged below the separator, in order to be then recovered, The HDECS equipment is expensive.



FigureI.17. Horizontal Drum Eddy Current Separator

c. Inclined Drum Eddy Current Separator(IDECS)

The Inclined Drum Eddy Current Separator (IDECS) consists of an inclined vertical rotating drum fitted with a succession of permanent magnets, alternately polarized N–S and S–N, directly attached to the shaft of an electric motor. The particles to be separated are brought into the field on an oblique trajectory, strike the drum and are deflected in the variable field under the effect of electrodynamic and mechanical interactions. Depending on their electrical conductivity, highly conductive and weakly conductive particles adopt different trajectories, which lead to their separation. The advantages of IDECS lies in its equipment cost which is lower and it can separate particles of small sizes (<5mm), When the distance between the metallic particles and the moving permanent magnets is small and the magnetic disc's revolution is high, the separator becomes more efficient [19].



FigureI.18. Inclined Drum Eddy Current Separator(IDECS)

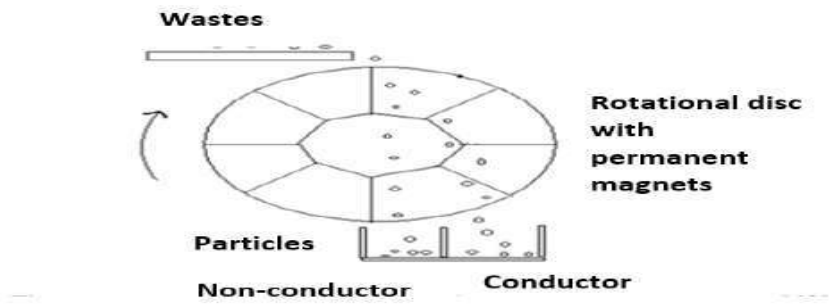
I-8-1-5. Rotating disc separators

A spinning non-magnetic disc with alternating magnetic segments is used to create the rotating disc separator device (RDS). Eddy currents are caused by a combination of a changing magnetic field and particle vertical motion. The change in magnetic induction in the vertical disc rotating.

eddy current separator is generated by two movements:

- The movement of the particle;

- The spinning of the discs.



FigureI.19. rotating disc separator

I-9. Conclusion:

This chapter categorizes the many kind of magnetic separators and their working principles and technical and magnetic features and their evolution. We presented different the various model of permanent magnets and their performances of magnetic field and her natural of materials. The presence of many types of industrial magnetic separators illustrates the significance importance of placed on ferrous and non-ferrous metal recovery in order to recover the huge volumes of trash generated in our everyday

Chapter II

Mathematical Formulation of Electromagnetic Phenomena

II-1 Introduction:

This chapter describes the establishing a mathematical model of separator structure that describes magnetic separator design physical processes by modeling entails, based on Maxwell's equations, which is a local partial differential equation model, formed by the combination of Ampere's theorem and Faraday's law in electromagnetic. The permanent magnets shape and intensities, and geometrical features are required for the modeling of any magnetic separation device. The solution of these equations, which are linked to the rules of magnetic behavior of separator in 2D, the finite element method is used to compute and visualize the distribution of magnetic form and magnitude properties surrounding a magnetic separator, in both static and rotating states and other parameters, with and without non-ferrous particles present [2].

II-2. Modeling of the magnetic drum separation problem:

II -2-1. Mathematical model governing the magnetic problem:

II -2-1-1. Applied magnetic field and model equation:

In electrical engineering, the set of electromagnetic phenomena is governed by the four Maxwell's equations that relate magnetic quantities to electrical quantities. They are given by:

$$\vec{\nabla} \wedge \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad \text{(II.1)}$$

$$\vec{\nabla} \wedge \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \text{(II.2)}$$

$$\vec{\nabla}.\vec{D} = \rho \qquad \text{(II.3)}$$

$$\vec{\nabla}.\vec{B} = 0 \qquad \text{(II.4)}$$

$\vec{H}$ is the magnetic excitation field, $\vec{J}$ is the current density. $\vec{E}$ is the electric field and $\vec{B}$ is the magnetic flux density, $\vec{D}$ is the electric induction and ρ is the volume density of electric charge.

The Maxwell system of equations given by ((II.2) -(II.4)) is indeterminate, it is appropriate to add to these equations, the relations expressing the properties of the materials which are called constitute relations or laws of behavior [20], these are:

$$\vec{B} = \mu\vec{H} \tag{II.5}$$

$$\vec{D} = \varepsilon\vec{E} \tag{II.6}$$

$$\vec{J} = \sigma\,\vec{E} \tag{II.7}$$

μ is the magnetic permeability ε and $\sigma$are the permittivity and the electrical conductivity respectively.

In our work, to allow simultaneous separation of conductive and magnetic particles, a dynamic magnetic field must be applied. To generate it, a permanent magnet drum driven by an electric motor was used. In the quasi-stationary approximation or approximation of electrical engineering$\left(\frac{\partial\vec{D}}{\partial t} = 0\right)$.

the system of reduced Maxwell equation related to our application is given as follows:

$$\vec{\nabla} \wedge \vec{H} = \vec{J} \tag{II.8}$$

$$\vec{\nabla} \wedge \vec{E} = -\frac{\partial\vec{B}}{\partial t} \tag{II.9}$$

$$\vec{\nabla}.\,\vec{B} = 0 \tag{II.10}$$

The laws of behavior associated with this system are given by:

$$\vec{J} = \vec{J}_{ind} = -\sigma(\vec{E} - \vec{v}_p \wedge \vec{B}) \tag{II.11}$$

$$\vec{B}=\mu\vec{H}+\vec{B}_r \tag{II.12}$$

$\vec{J}_{ind}$is the density of induced currents $\vec{v}_p$is the velocity of the particle and $\vec{B}_r$is the remanent magnetic flux density.

The relation of the conservation of magnetic flux (II.10) implies that there is a magnetic vector potential $\vec{A}$ such as:

$$\vec{B}=\vec{\nabla}\wedge\vec{A} \tag{II.13}$$

Carrying equation (II.13) into (II.9) we get:

$$\vec{\nabla}\wedge\left(\vec{E}+\frac{\partial\vec{A}}{\partial t}\right)=\vec{0} \tag{II.14}$$

Equation (II.14) implies that there is an electric scalar potential *V* such as*:*

$$\vec{E}+\frac{\partial\vec{A}}{\partial t}=-\vec{\nabla}V \tag{II.15}$$

It follows that [2,21]:

$$\vec{E}=-\vec{\nabla}V-\frac{\partial\vec{A}}{\partial t} \tag{II.16}$$

The substitution of equations (II.11) and (II.12) in equation (II.8) with the consideration of equations (II.13) and (II.16) leads to a formulation *A* - *V* of the PDE equation given by the following system:

$$\begin{cases}\vec{\nabla}\wedge\left(\frac{1}{\mu}\vec{\nabla}\wedge\vec{A}\right)+\sigma\left(\frac{\partial\vec{A}}{\partial t}-\vec{\nabla}V\right)-\sigma\left(\vec{v}_p\wedge\left(\vec{\nabla}\wedge\vec{A}\right)\right)=\frac{1}{\mu}\vec{\nabla}\wedge\vec{B}_r\\ \vec{\nabla}\cdot\left(\varepsilon\vec{\nabla}V\right)+\vec{\nabla}\cdot\left(\varepsilon\frac{\partial\vec{A}}{\partial t}\right)=0\end{cases} \tag{II.17}$$

The system (II.17) does not have a unique solution, if $\vec{A}$ is a solution, any field of type $(\vec{A} + \vec{\nabla} f)$ where f is any scalar function is also a solution of (II.17). To ensure the uniqueness of the solution, we must add a scalar equation, called gauge condition [20]. Commonly used gauges are the coulomb gauge($\vec{\nabla} \cdot \vec{A} = 0$) and the Lorentz gauge ($\vec{\nabla} \cdot \vec{A} = -\mu\sigma V$).

To solve the system equation (II.17), we associate boundary conditions that can be of Dirichlet or Newman type or mixed.

- Homogeneous Dirichlet : $A = 0$
- Inhomogeneous Dirichlet : $A = Cte$
- Homogeneous Newman :$\frac{\partial A}{\partial n} = 0$
- Newman not homogeneous : :$\frac{\partial A}{\partial n} = Cte$
- Dirichlet-Newman (Robin) :$aA + b\frac{\partial A}{\partial n} = g$

a and *b* are constants [2,21].

On a boundary of separation between two environments 1 and 2, the electromagnetic fields could be discontinuous and are therefore not differentiable. However, it is possible to derive so-called passage or transmission conditions making it possible to express the relations between two quantities on the boundaries of the two environments [20].
The continuity of the normal component of magnetic induction.

$$\vec{n} \cdot \left(\vec{B}_2 - \vec{B}_1\right) = 0 \qquad \text{(II.18)}$$

The continuity of the tangential component of the electric field.

$$\vec{n} \wedge (\vec{E}_2 - \vec{E}_1) = \vec{0} \qquad \text{(II.19)}$$

Discontinuity of the normal component of electrical induction.

$$\vec{n} \cdot \left(\vec{D}_2 - \vec{D}_1\right) = \rho_s \qquad \text{(II.20)}$$

The discontinuity of the normal component of the magnetic field

$$\vec{n} \wedge \left(\vec{H}_2 - \vec{H}_1\right) = \vec{J}_s \qquad \text{(II.21)}$$

$\vec{n}$ is the vector normal to the surface$\rho_s$and $\vec{J}$ are respectively the densities of charges and of surface currents.

II 2-1-2. Forces of magnetic origin applied to particles:

A) Force applied to the magnetic particle:

When a ferromagnetic particle is subjected to an external magnetic field it becomes magnetized, the interaction between this magnetization and the applied magnetic field results in a force of an attractive nature that forces the magnetic particle to deviate and move closer to the source of the field.

For a solid ferromagnetic particle of volumeV_P, the applied magnetic force is given by [20] :

$$\vec{F}_m = \mu_0 V_P (\vec{M} \cdot \vec{\nabla})\vec{H} \tag{II.22}$$

For a three-dimensional configuration, and in a Cartesian coordinate system, the force applied to a magnetic particle is given by [20]:

$$\vec{F}_m = \mu_0 V_P \left(M_x \frac{\partial H_x}{\partial x} + M_y \frac{\partial H_x}{\partial y} + M_z \frac{\partial H_x}{\partial z}\right)\left(H_x \vec{i} + H_y \vec{j} + H_z \vec{k}\right) \tag{II.23}$$

$$\begin{cases} \vec{F}_{mx} = \mu_0 V_P \left(M_x \dfrac{\partial H_x}{\partial x} + M_y \dfrac{\partial H_x}{\partial y} + M_z \dfrac{\partial H_x}{\partial z}\right) \\ \vec{F}_{my} = \mu_0 V_P \left(M_x \dfrac{\partial H_y}{\partial x} + M_y \dfrac{\partial H_y}{\partial y} + M_z \dfrac{\partial H_y}{\partial z}\right) \\ \vec{F}_{mz} = \mu_0 V_P \left(M_x \dfrac{\partial H_z}{\partial x} + M_y \dfrac{\partial H_z}{\partial y} + M_z \dfrac{\partial H_z}{\partial z}\right) \end{cases} \tag{II.24}$$

Here$\vec{M}$ represents the volume magnetization of the particle, it is given by [20]:

$$\vec{M} = \left(\frac{B_x}{1+\chi n_1}, \frac{B_y}{1+\chi n_2}, \frac{B_z}{1+\chi n_3}\right) \tag{II.25}$$

χ is the magnetic susceptibility, it is given by:

$$\chi = u_r - 1 \tag{II.26}$$

n_1, n_2 end n_3 are called the demagnetization factors. They depend on the geometric shape of the particle. For a spherical particle $n_1 = n_2 = n_3 = \frac{1}{3}$.

By substitution in equation (II.25) and taking into account equation (II.26) we find:

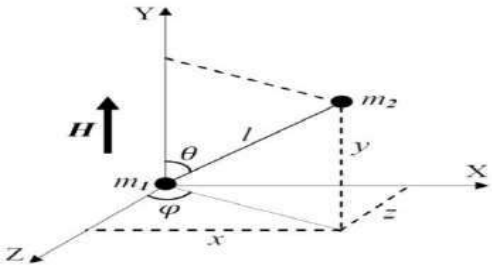
$$\begin{cases} M_x = \frac{3\mu_r(\mu_r-1)}{(\mu_r+2)} H_x \\ M_y = \frac{3\mu_r(\mu_r-1)}{(\mu_r+2)} H_y \\ M_z = \frac{3\mu_r(\mu_r-1)}{(\mu_r+2)} H_z \end{cases} \quad \text{(II.27)}$$

For a cylindrical particle $n_1 = 0,\ n_2 = n_3 = \frac{1}{2}$ After simplification, we get:

$$\begin{cases} M_x = \mu_r(\mu_r - 1)H_x \\ M_y = \frac{2\mu_r(\mu_r-1)}{(\mu_r+1)} H_y \\ M_z = \frac{2\mu_r(\mu_r-1)}{(\mu_r+1)} H_z \end{cases} \quad \text{(II.28)}$$

B) Inter-particle force (Dipole-Dipole) between particles:

In the absence of the magnetic field, the mono-domains that form a magnetic particle carry randomly oriented permanent magnetic moments of such kinds that the total dipole moment of the particle is zero. In the presence of the magnetic field, all the magnetic moments of the mono-domains are oriented in the direction of the applied field thus creating a global magnetic moment for the particle [20]. Particle magnetized behave like magnetic dipoles, the interaction between the field magnetic created by each dipole and neighboring dipoles results in a force of nature attractive called magnetic interaction force. A representation of a pair of dipoles magnetic fields in a three-dimensional coordinate system is shown in Figure II.1.



FigureII.1 System of two neighboring magnetic spherical particles [20]

The three components of the force of interaction between particles are given by [20]:

$$\begin{cases} F_{DDx} = \frac{|m_x{'}|^2}{4\pi\mu}\frac{3(5\,cos^2\,\theta-1)\sin\theta\sin\varphi}{l^4} \\ F_{DDy} = \frac{|m_y{'}|^2}{4\pi\mu}\frac{3(5\,cos^2\,\theta-3)\cos\theta}{l^4} \\ F_{DDz} = \frac{|m_z{'}|^2}{4\pi\mu}\frac{3(5\,cos^2\,\theta-1)\sin\theta\cos\varphi}{l^4} \end{cases} \quad \text{(II.29)}$$

m_x' , m_y' and $m_z'$are the moments of the magnetic dipoles, they are given by [20]:

$$\begin{cases} m_x^{'} = \frac{12\mu\pi xy\beta^2 r^6 H}{(l^2+r^2)^{\frac{5}{2}}(1-4\pi\mu\beta r^3)} \\ m_y^{'} = \frac{4\mu\pi xy\beta r^3 H}{(1-4\pi\mu\beta r^3)} \\ m_z^{'} = \frac{12\mu\pi xy\beta^2 r^6 H}{(l^2+r^2)^{\frac{5}{2}}(1-4\pi\mu\beta r^2)} \end{cases} \quad \text{(II.30)}$$

μ represents the magnetic permeability of the medium $\beta = \frac{\mu_k - \mu_k}{\mu_k+2\mu_r}$, $\mu_k$and μ_r are respectively the relative magnetic permeabilities of the particles and the medium r is the radius of the magnetic dipole and H represents the intensity of the applied magnetic field.

C) Force applied to the conductive particle:

When a conductive particle is subjected to a time-varying magnetic field, it will be the seat of an electromotive force, which leads to the creation of induced currents in the particle. The interaction between the density of these currents and the magnetic field dynamic applied results in a magnetic force of a repulsive nature called the force of Lorentz which forces the particle to move away from the source of the field. For a solid particle volume V_p, the Lorentz force is given by [20]:

$$\vec{F}_L = \left(\vec{J} \wedge \vec{B}\right) \cdot V_P \qquad \text{(II. 31)}$$

For a three-dimensional configuration, the Lorentz force is expressed as:

$$\begin{cases} F_{Lx} = V_P\left(J_y B_Z - J_z B_y\right) \\ F_{Ly} = V_P\left(J_z B_x - J_x B_z\right) \\ F_{Lz} = V_P\left(J_x B_y - J_y B_x\right) \end{cases} \qquad \text{(II.32)}$$

II -3. Different methods for solving partial differential equations:

The objective of applying numerical discretization methods is to simplify the resolution of a system of differential equations in an area of study to a system of algebraic equations whose solution leads to the determination of electromagnetic fields and displacement. We will mention some of the different techniques used to solve a system of partial differential equations.

II -3-1. The finite element method(FEM):

In order to solve the proposed mathematical problem, we use the COMSOL 4.3 Multiphysics software based on numerical finite element method (FEM), to find approximate solutions of partial differential equations of magnetic domain.

The Finite Element Method (FEM) is a sophisticated computational technique for solving differential and integral equations in a variety of engineering and applied sciences domains [22].

This method entails dividing the domain of interest into finite elements and using interpolation functions to approach the unknown in each element. These functions are usually first- or second-degree Lagrange polynomials. The interpolation in an element is done according to its nodal values, which imposes the unknown's continuity on the element's interfaces.

II -3-1-1. Principle of the finite element method

It is a numerical method used to solve mathematical linear differential equation.

The principle of the FEM lies in the division of the elementary domain of finite dimensions on each domain called finite element, the unknown function is approached by a tooth polynomial the degree can vary from one application to another.

The main stages of construction of a finite element method are the following:

● Discretization of the continuous environment, representing the field of study in sub-field (element).

● Construction of the nodal approximation by subdomain.

● Calculates elementary matrices (for each element) corresponding to the integral from of the problem.

● Assembly of elementary matrices taking into account the boundary conditions

● Solving the equation system.

● solving the equation system.

There are different types of elements:

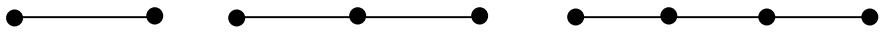
- linear element (1D).
- Surface element (2D).

- Volume element (3D) [2].

In our case, the field of study, which is two-dimensional, we often meet with linear, quadratic or cubic elements. To lead to a better accuracy of the solution, one proceeds to refine the mesh see figure II.2.

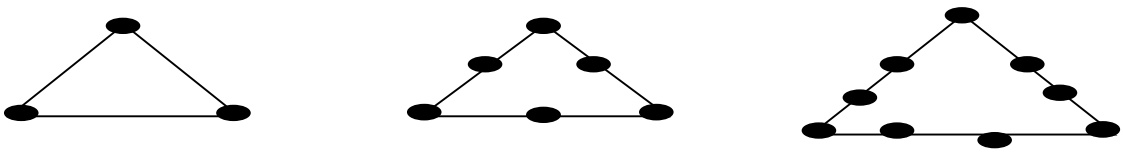
The figure II.2show the discretization of the study domain.

➢ One-dimensional problem (straight element)



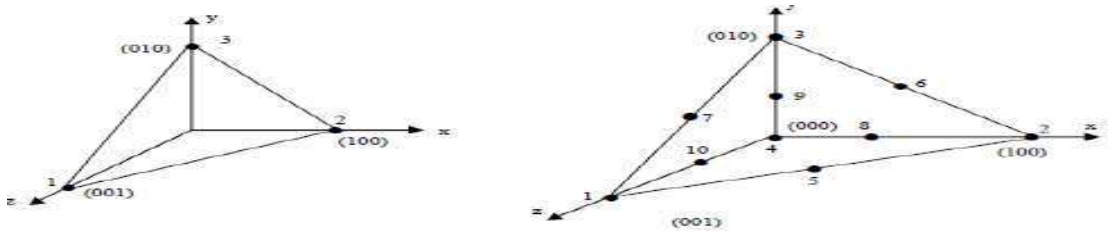
Linear (02 nodes) quadratic (03 nodes) cubic (04 nodes)

➢ Two-dimensional problem (triangle or quadrilateral)



a) Linear element (03 nodes) b) quadratic (06 nodes) c) cubic (09 nodes)

➢ Three-dimensional problem



Linear element (04 nodes) Quadratic element (10 Nodes)

Figure II.2 Discretization of the study domain (mesh) [2, 23]

II -4. Boundary conditions:

The boundary conditions allow the calculation of the vector potential expression constants established in each constitutive zone of the machine. Two types of boundary conditions can be distinguished :

- Boundary conditions of Dirichlet ($A\ (r,\theta = 0)$ or Newman type (∂A (r,θ)/∂r = 0)
- Conditions at the boundaries of environmental studies.

In a fixed reference study frame, two types of conditions are distinguished at the limits of separation between two media (i) and (i + 1):

II -4-1. Numerical analysis:

Because of the complexity of electromagnetic systems (3D geometry, non-linearity, coupled phenomena), Maxwell's equations generally do not present an analytical solution.

It is, therefore, necessary to use numerical methods by making space and local quantities discrete. The finite element method appears to be best adapted to solving this type of problem. Yet it is difficult to make discrete the elements contained in the mathematical structure generated by partial differential equations [24]. The basic concept of the finite element method is the subdivision of the mathematical model into disjoined components of simple geometry called Finite Elements. The behavior of each element is expressed in terms of a finite number of degrees of freedom. The behavior (response) of the mathematical model is considered, approximately, that of the discrete model obtained by connecting or assembling the elements

$$[K^e]\{U^e\} = \{F^e\} \qquad \text{(II.33)}$$

Or K^eElemental rigidity matrix, U^e Degree of freedom (displacement) nodal and F^e Force applied to the elementary rigidity matrix nodesIt is very interesting to have a simulation environment that includes the possibility ofadding different physical phenomena to the studied model. Accordingly, the study used COMSOL Multiphysics. This modular finite element numerical calculation software enables the modelling of a wide variety of physical phenomena characterizing a real problem. It can manage complex geometries and so is a design tool [4].

II -5. Finite Modeling of Permanent Magnets:

The hysteresis characteristic equation for the permanent magnet can be inserted into amperes law (without displacement currents) and then discretized. This is done to get equation II.34 [25].

$$\nabla \times [v\mathrm{B} - \mathrm{Hc}] = \mathrm{J}_{ext} \qquad (\mathrm{II.}\,34)$$

The coercive force of the permanent magnet (excitation) in equation II.34can be moved over to the right side of the get equation II.35.

$$\nabla \times (v\mathrm{B}) = \mathrm{J}_{ext} \quad + \nabla \times Hc \qquad (\mathrm{II.}\,35)$$

The equation can also be solved with respect to the magnetization vector [25], as in equation II.36.

$$\nabla \times (v\mathrm{B}) = \mathrm{J}_{ext} + \nabla \times (v\mu_0\mathrm{M}) \qquad (\mathrm{II.}\,36)$$

In the same way, it is possible to solve the equation with respect to the magnetic vector potential.

$$\nabla \times (v\nabla \times \mathrm{A}) = \mathrm{J}_{ext} + \nabla \times \mathrm{Hc} \qquad (\mathrm{II.37})$$

In 2D analysis, there is no excitation from the permanent magnet in the z-direction. The curl of the excitation can then be simplified in two dimensions.

$$\frac{\partial}{\partial x}\left[v\frac{\partial A_z}{\partial x}\right] + \frac{\partial}{\partial y}\left[v\frac{\partial A_z}{\partial y}\right] = -\mathrm{J}_{ext} + \frac{\partial Hc_x}{\partial y} - \frac{\partial Hc_y}{\partial x} \qquad (\mathrm{II.38})$$

The only region where there is a coercive force is in the permanent magnet region, but the sources of diffusion applies only at the boundaries of the PM where Hc changes to zero. It is easy to see that the permanent magnet has a current winding equivalent (*HI=NI*).

II 5-1. Mathematical models:

To compute the dynamic magnetic field required to separate magnetic and conductive particles and to take into account the effect of the induced currents related to the variation of the field and the displacement of the conductive particles we solved for each rotation step of the drum the equation given by [26,23]:

$$\vec{\nabla}\left(\frac{1}{\mu}\vec{\nabla}\times\vec{A}\right)+\sigma\left(\frac{\partial\vec{A}}{\partial t}-\vec{v}_p\times\vec{B}\right)=\frac{1}{\mu}\left(\vec{\nabla}\times\overrightarrow{B_r}\right) \quad \text{(II.39)}$$

Where, $\vec{A}$ is the magnetic vector potential, $\vec{B}$ is the magnetic flux density at the particle site, $\overrightarrow{B_r}$ is the residual magnetic flux density of the magnets, μ is the magnetic permeability, σ and $\vec{v}$ are respectively the particle electrical conductivity and displacement velocity.

The magnetic force applied on a magnetic particle is given by [24,27):

$$\overrightarrow{F_m}=\mu_0\int_{vp}(\vec{M}\cdot\vec{\nabla})\vec{H}dv \quad \text{(II. 40)}$$

Where, $\vec{H}$is the magnetic field strength in the particle site, $\vec{M}$ is the particle magnetization, μ_0 is the magnetic permeability of vacuum and v_p, is the particle volume.

The current density induced in the conductive particle related to the variation of the applied field is given by [28]:

$$\vec{J}_F=-\sigma\frac{\partial\vec{A}}{\partial t} \quad \text{(II.41)}$$

The displacement of the particle in the applied field leads to the generation of an additional component of the induced currents given by [29]:

$$\vec{J}_{Fa}=\sigma\left(\vec{v}_p\times\vec{B}\right). \quad \text{(II. 42)}$$

The resulting force applied on the conductive particle is given by [29]:

$$\vec{F}_L = \left(-\sigma\left(\frac{\partial\vec{A}}{\partial t} - \vec{v}_p \times \vec{B}\right) \times \vec{B}\right) \qquad \text{(II. 43)}$$

To compute the trajectory of a moving particle one can solve the dynamic equation given by [30]:

$$\sum \vec{F} = m_p \frac{\partial \vec{v}_p}{\partial t} \qquad \text{(II. 44)}$$

Where,m_p, is the particle mass and $\vec{F}$ is the resultant of the applied forces.In addition to the forces applied to the particles given by Eqs (II.40) and (II.43), we can mention the force of mechanical interaction of the particles with the conveyor belt and the magnetic dipole-dipole interaction between ferromagnetic particles. To solve the motion equation (II.44), we have only considered the magnetic, Lorentz and the gravity forces.

II -6. Program structure:

The following picture shows the structure of the program adopted in our work represented in three successive operational blocks based on Maxwell's equations and the various model data(figure II.3).

Figure II.3: different program blocks [2]

The program is composed of the following:

A) Input Block

This block includes the cable model database for each stage of the construction:

● Geometric dimension parameters
● Material properties (permeability, permittivity and electrical conductivity)
● Equations accompanying the field of study
● Number and size of mesh element

B) Resolution block (computation)

This block receives the input data for the purpose of inserting and processing it into a system that includes:

● Generate a partial differential equation based on Maxwell's equation using one dependent variable as a out-of-plan.

● Apply the finite element method algorithm for solving the differential equation then calculate the approximate value of the physical unknown in each element.

C) Output block

Here, simulation results that represent solutions to the system of equations and resulting

Statistics are displayed and shown, whether in graphic or digital form.

After simulation the results can be exported even to the MATLAB editor.

The COMSOL Multiphysics software uses the FEM to help model and simulate electromagnetic fields in several applications, (i.e. engine, cable, coil, power lines), and solve linear and nonlinear equations and complex models. Many steps characterize the software simulation:

− Geometry generation model;

− The material declaration of each subdomain;

− Physics model and equations (interface conditions, the electrical and physical properties);

− Generating mesh;

− Study (stationery, frequency, temporal);

− Solve and computation; − Plot and results visualization.

II -7. Conclusion:

In this chapter, we have given the electromagnetic model by partial differential equations (PDE), for our case we will use the finite element method in 2D by the exploitation of the COMSOL software for the resolution of the model of a magnetic separator.

Chapter III

Simulation of vertical eddy current separator

III-1. Introduction:

In this chapter we study and implement the separator device composed by several permanent magnets with non-ferrous particles in numerical software based on the previous model of chapter II. The numerical modeling and simulation under COMSOL 4.3 Multiphysics with Matlab software based on finite element method (FEA) to solve partial differential equations and many problems: such as electrostatics, magnetostatics, electrodynamics, fluid flow, and material deformation. The simulation result help to show the magnetic field near and around of the magnetic separator in static and dynamic state (rotate).

III-2. Definition of COMSOL:

COMSOL Multiphysics software use numerical simulation based on the finite element method. This software makes it possible to simulate many applications in engineering, and especially coupled phenomena or Multiphysics simulation.

The different stages of the modeling process are:

- Define the geometry
- Material properties
- Adding Meshes
- Adding Physics
- Solve and obtain results

III-3. COMSOL 4.3 interface:

The COMSOL interface contains four sections summarized as follows:

III-3-1. The Model Builder:

The Model Builder is a tool for defining a model and its components, such as how to solve it, how to analyze the results, and how to create reports. you accomplish this by creating a model tree. The model object, which stores the state of the model, including settings for geometry,

mesh, physics, boundary conditions, studies, solvers, postprocessing, and visualizations, is reflected in the model tree [31].

III-3-2. Settings Window:

It's the main window for inputting all of the model's requirements, such as geometry dimensions, material properties, boundary conditions, and initial conditions, as well as any other information the solver will need to run the simulation [31].

III-3-3. Graphics Window:

These are the graphical output windows, The Graphics window presents interactive graphics for the Geometry, Mesh, and Results nodes. Operations include rotating, panning, zooming, and selecting [31].

III-3-4. information Windows:

During the simulation, the Information windows will display critical model information such as the solution time, progress, mesh statistics, solver logs, and, if available, results tables.

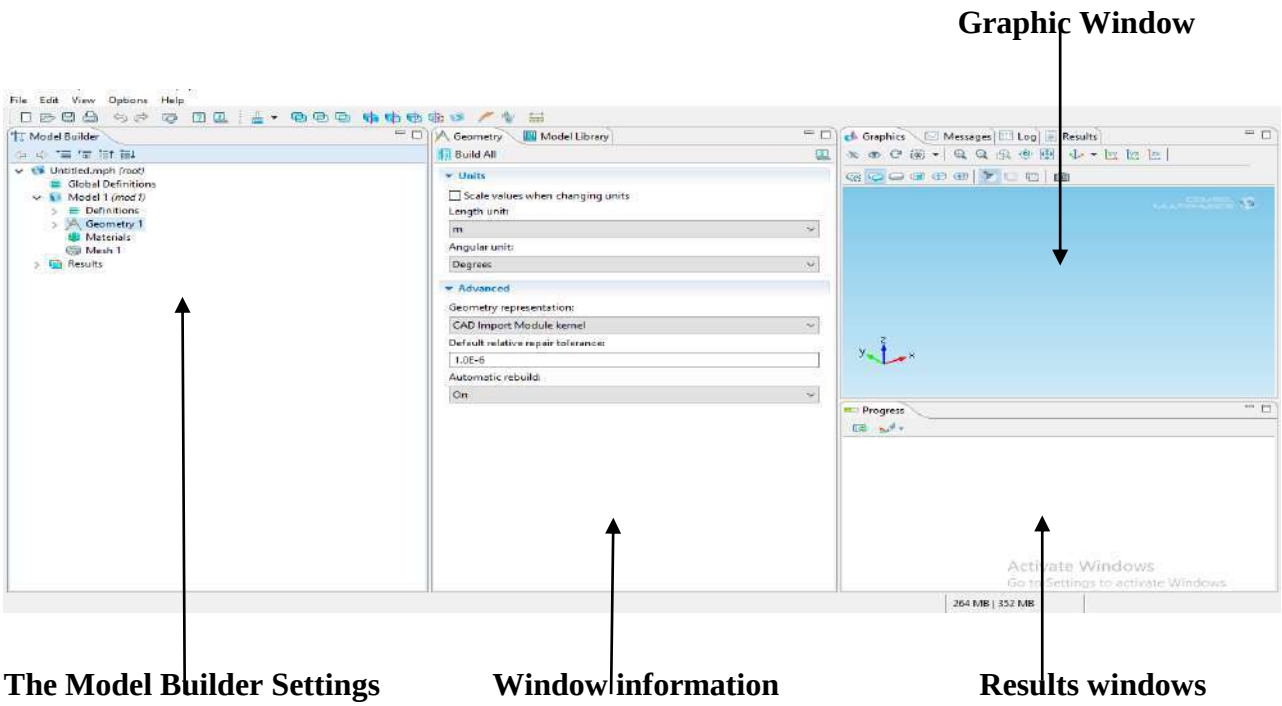
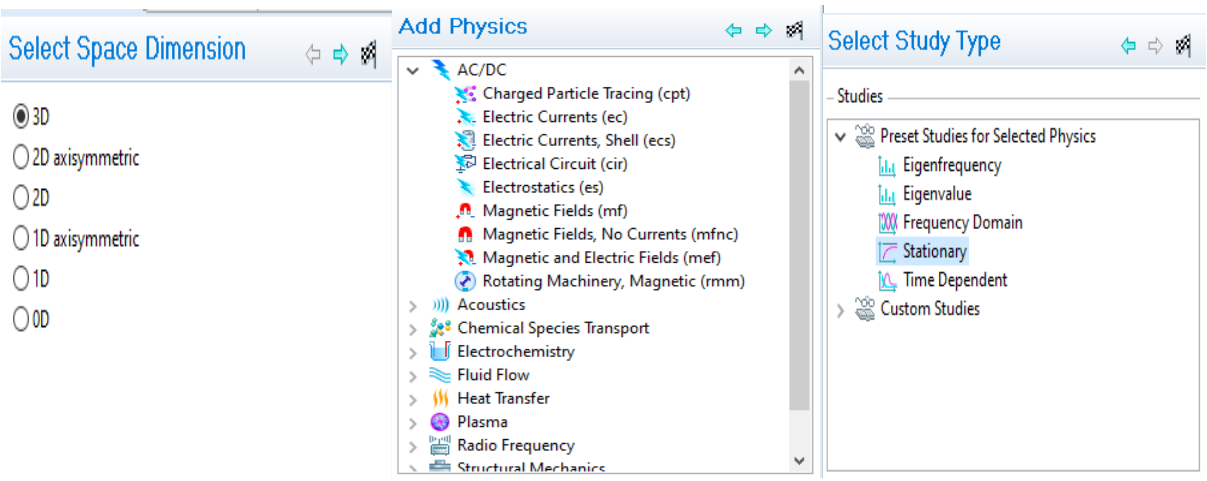


Figure III.1 The COMSOL 4.3 interface

III-4. Model creation in 3D geometry:

Create a COMSOL Multiphysics model for that dimension of space as the initial stage in generating a 3D geometry model.

1) We begin by choosing the model component's space dimension.
2) One or more physics interfaces can be added. They've been arranged into a number of physics branches to make them easier to find.
3) Choosing the Study type that corresponds to the solver that will be utilized in the calculation.



a) Dimension Space b) field of study c) study type

Figure III.2 Construction of the basic model structure

III-4-1. The construction of geometry :

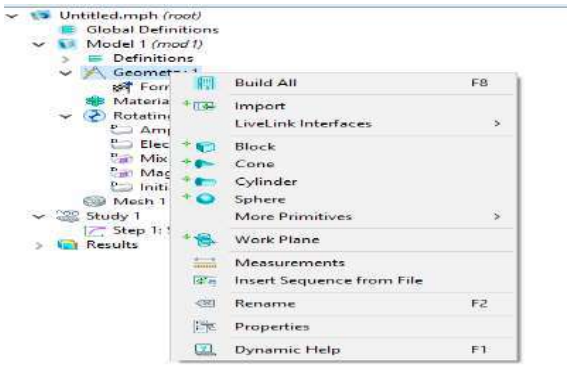


Figure III.3 Geometry drawing menu

- **Geometry drawing**

1) In the Model Builder window, right-click **Geometry 1** and select **Cylinder** or other shape.

- In the "cylinder" settings window, locate the Section and Size

2) In the Model Builder window, right-click **Geometry 1** and select **Cylinder2**

- In the "cylinder" settings window, locate the Section and Size

3) In the Model Builder window, right-click **Geometry 1**select**Cylinder3** right-click **Geometry 1**under**Boolean operations**select **difference** and Select cylinder 1.3

a) size cylinder1 b) size cylinder2 c) size cylinder3

Figure III.4 Declaration of dimensions

Figure III.5 the model of three cylinders

4) In the Model Builder window, right-click **Geometry 1** and select **Cylinder4**

- right-click **Geometry 1**select transforms and select rotate

5) Click the **Build all** button

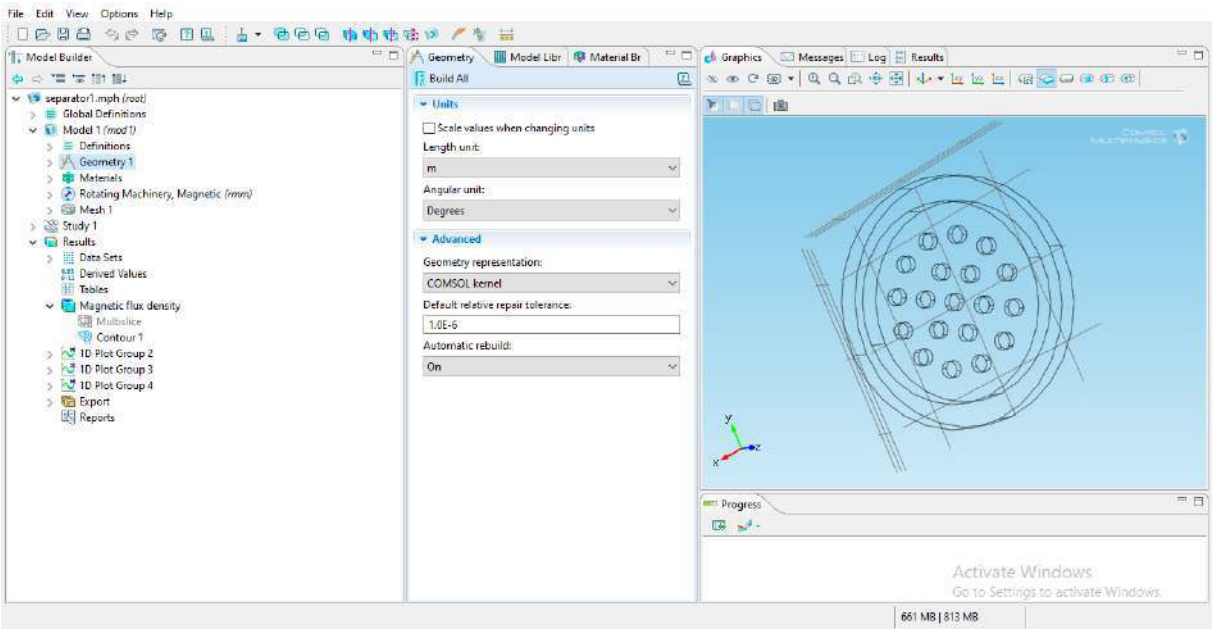


Figure III.6 The geometry of a magnetic separator in 3D

III-4-2. Materials :

In a Component node, the Materials node stores the material properties for all physics and geometrical domains[11].

1) In the Model Builder, right-click **Materials** and select **open Material browser**

2) In the Add Material window, expand the Built-In materials folder and locate Air. Right-click air and select Add material to model.

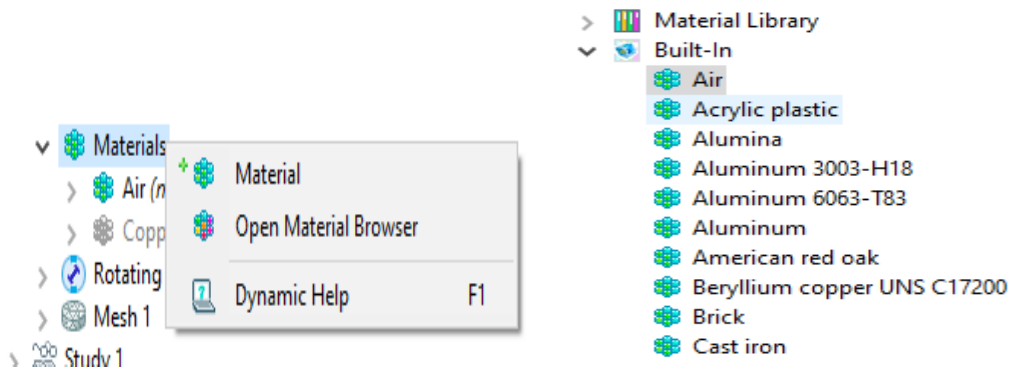


Figure III.7the choice of materials

III-5. Mesh :

The easiest way to mesh is to create an unstructured tetrahedral mesh, which is perfect. The mesh is created by default, in most cases the parameters are studied in order to size the mesh

1) In the Model 1 window - right click mesh 1 and choose the type of **UserControlledMesh**
2) In the model under, Model 1>mesh 1 click on Size, click the **predefined** button to modify the dimensions of the mesh

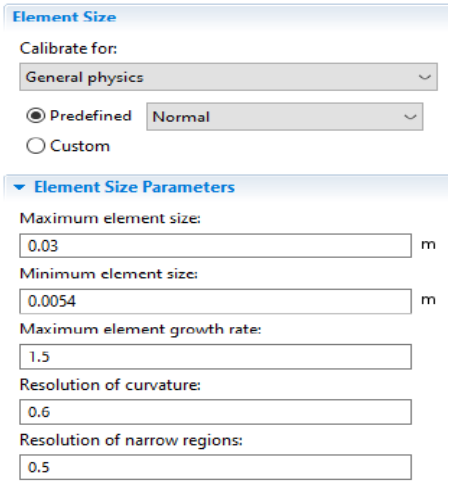


Figure III.8 Element size

3) Click the build All button in the Settings window to create the mesh as shown in this figure:

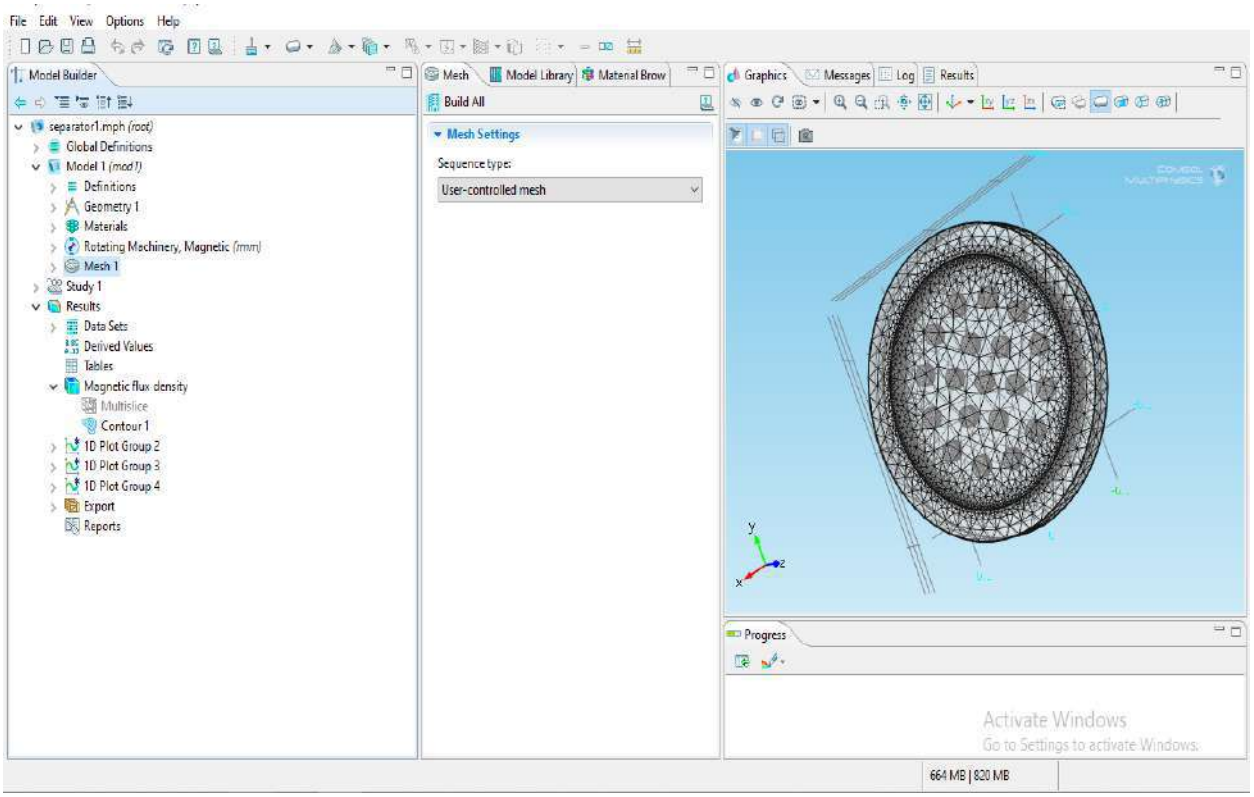


Figure III.9 Mesh of the field of study

III-6. Study:

In the Study 1 window, locate the Steps of the study section, it allows us to declare the temporal or frequency parameters that characterize the study environments in order to calculate the electrical or mechanical magnetic parameters according to known or unknown variables.

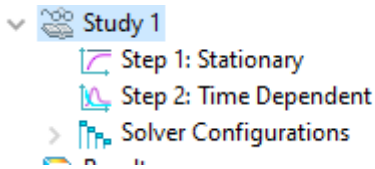


Figure III.10 The choice of study variable

III-7. Results :

In the "model builder" window, right-click on "results" and choose the type of representation of the results, for example surface or contour, etc.

III-7-1: magnetic induction

Right-click on results and choose Magnetic Flux Density> contour1. The result you should get is shown in the following figureIII.11:

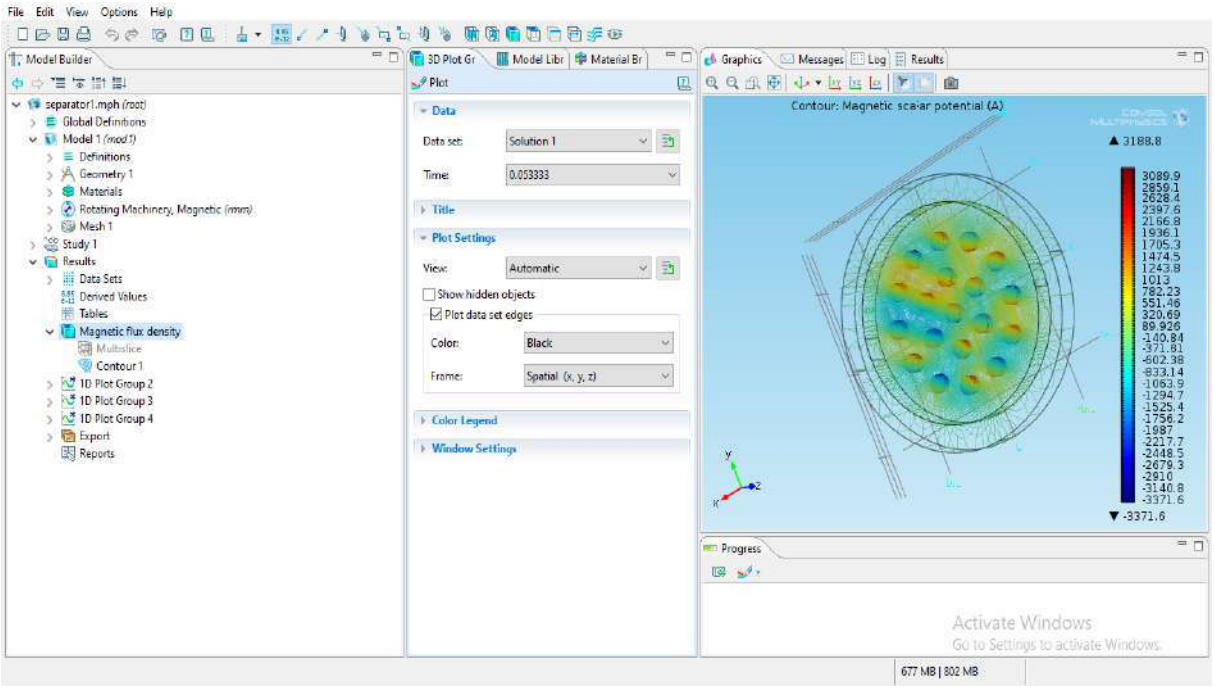


Figure III.11 magnetic induction

- **Representation of curves**

The instruction "**1D plot group 1**" allow us to represent the curves or measurements in points or at ends according to time.

In the 'model builder' window, right-click on 'results' and choose '1D plot group 2'

"1D plot Group 2" and choose "Line graph 1"

III-8. Principe of our Eddy current magnetic separator:

In our study, the eddy current separator consists of rotational magnetic vertical disk covered with altering permanents magnets, the system driven by an engine, see figure III.12. The

separator turns with rotational speed he generates the alternating magnetic field, when the non-ferrous particle flow in the magnetic field an eddy current is created in these particles and they will be ejected by repulsive magnetic force (Lorentz force), the plastic particles fall with gravity force in the collector [32,31].

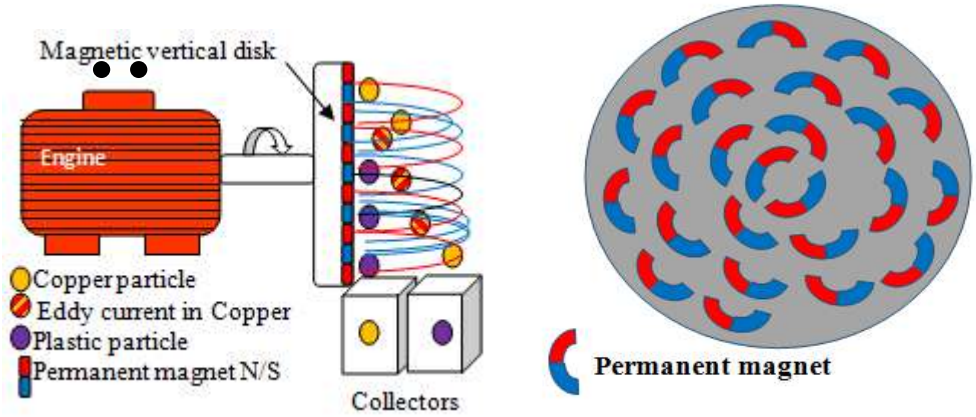
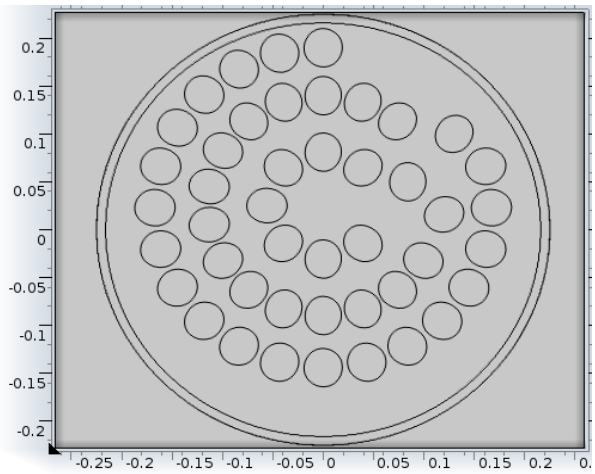


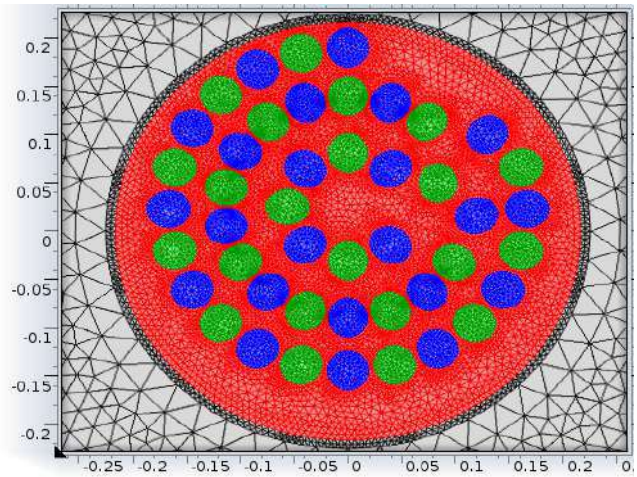
Figure III.12 rotational eddy current vertical disk.

III-9.2D Model implementation in FEM software:

The computation of flux density and magnetic field distribution by finite element method (FEM) analysis in COMSOL Multiphysics it is based on techniques meshing the separator geometry [31]. This method based on the number of degree of triangular elements, boundary element, numbers of vertex elements are shown in **Figure III. 13-a.**



A- Circular permanent magnet



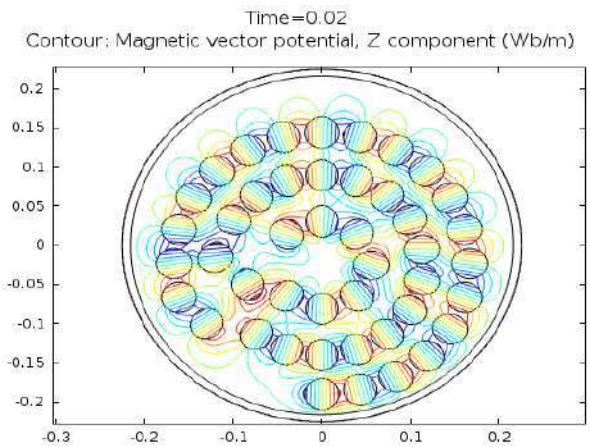
B- Mesh of model with FEM using COMSOL software

Figure III.13 proposed model of eddy current separator

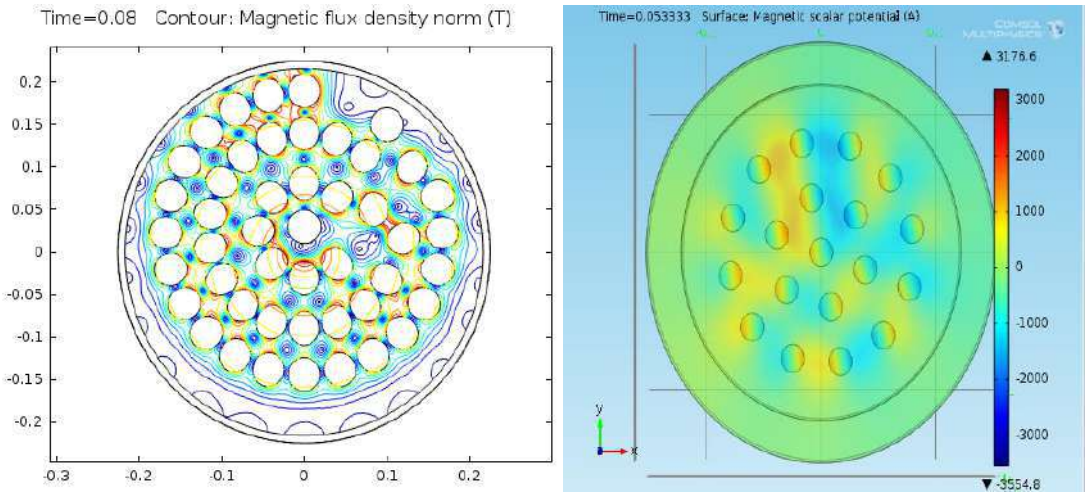
Figure III.13 shows the refine mesh of separator (vertical magnetic disk with permanent magnet and air) to have better accuracy than possible.

III-10. Simulation results:

Simulation results of separator type (design of the shape and number n of magnet, pole pairs) with permanents magnets of different polarity are shown in Figure III.14. The magnetic distribution lines around the device represent the interaction between polarities of permanents magnets, were studied numerically using the finite elements method with the COMSOL Multiphysics software.



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



b- Magnetic flux density norm (T) c- magnetic scalar potential(A)

Figure III.14 Magnetic characteristics of separators

Figure III.14 represents the distribution of the magnetic vector potential A, magnetic flux density and magnetic scalar potential nears the magnetic disk in static state. This result shows a high concentration around the permanent magnets placed in vertical disk, this distribution becomes small proportions moving away from the separator.

III-10-1. Measurement of the magnetic flux density:

The measurement of the magnetic flux density variation in central axes for the configuration shown in figure III.14:

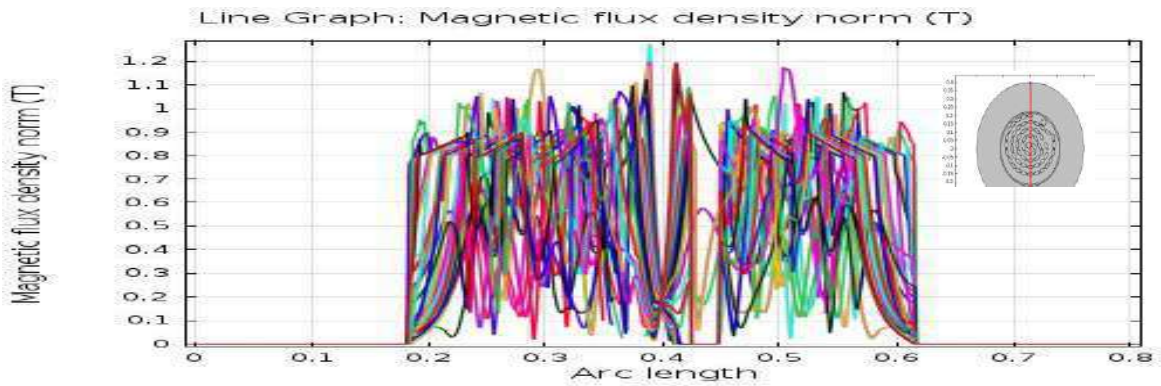
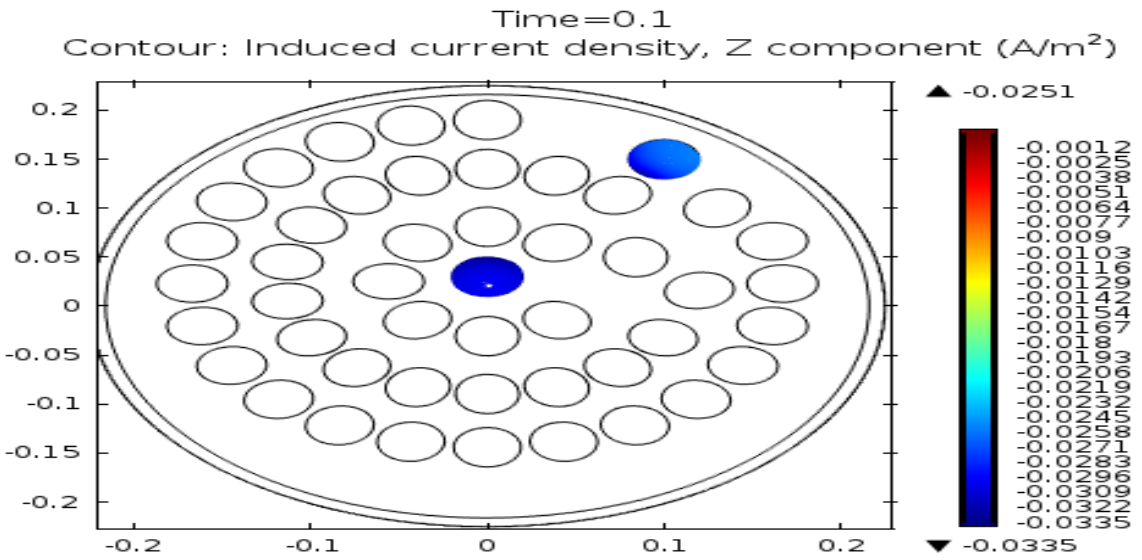


Figure III.15 Variation of the magnetic flux density according to central distance for configuration

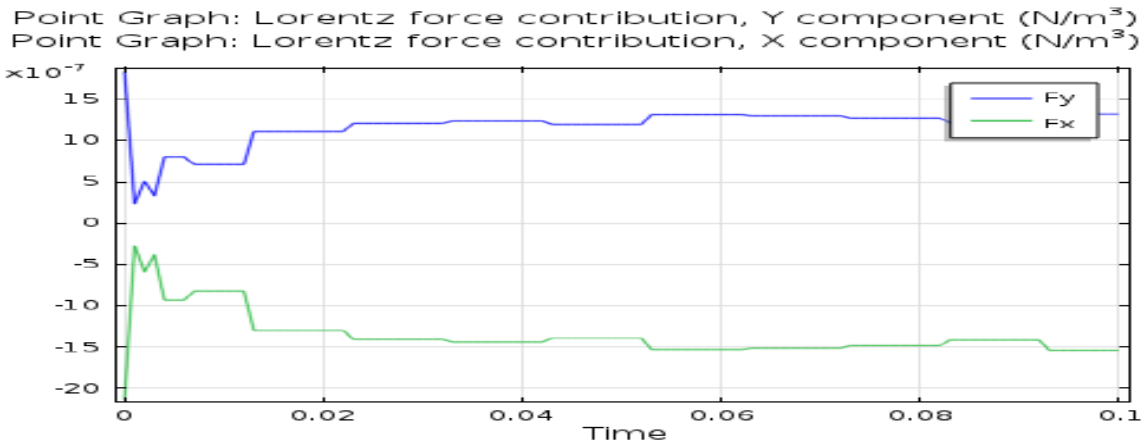
Figure III.15 represent the different waveform and shape, magnitude affected by the nature of permanent magnets caused by the geometries and number with magnetic induction 0.84T and speed of 1500 rpm.

III-10-2. Presence of non-ferrous particles near the separator:

The permanent magnet multiplication numbers give an important induced current in the particles; these cause the great and rapid variation of magnetic field.



A-Induced current in copper particles



B-Lorentz force exerted on circulars copper particles

Figure III.16 Magnetic induction and force on circulars copper particles

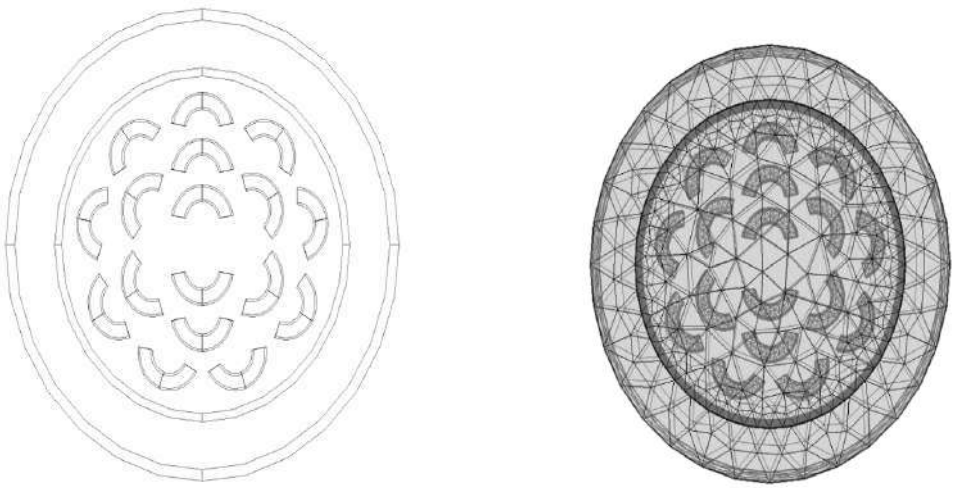
The initial alternating magnetic field of the separator induces a second opposing magnetic field in the nonferrous particles. This phenomenon of electromagnetic induction is based on Faraday's law. The variation of magnetic flux induces current in the particles by skin effect.

The numeric simulation of Eddy current in particles is very important because: the distribution of induced current will depend on the size and volume and will affect the strength

of Lorentz. Figure III.16 shows eddy current in 2D circular non-ferrous particles for different radii R 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 articles increase.

Eddy Current Separation based on Lorentz ejection force produced by interaction between permanent magnet of disk and non-ferrous particles by the opposition of particles magnetization and first field. The computation of the maximum values of magnetic force in particles is represented in Figure III.16 From result we conclude: Lorentz force exerted on circulars copper particles is very relative to eddy current. This force is important parameters in separation process and she affects directly the rate of separation and purity of sorting, see figure III.16.

III.11 3D Simulation of vertical rotational magnetic disk

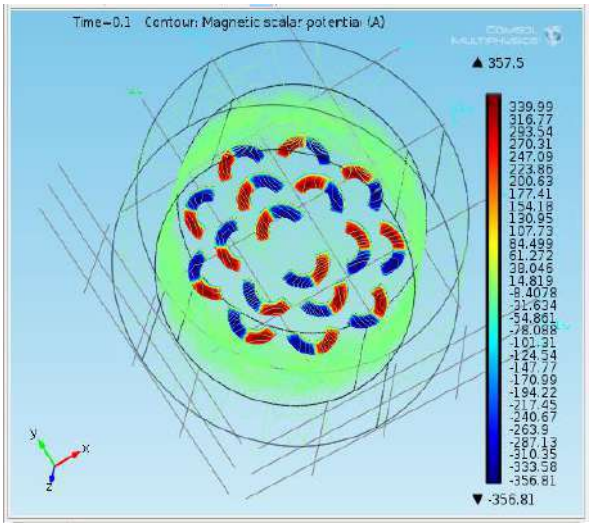


a- Elliptical permanent magnet b- Mesh of model with using Comsol software

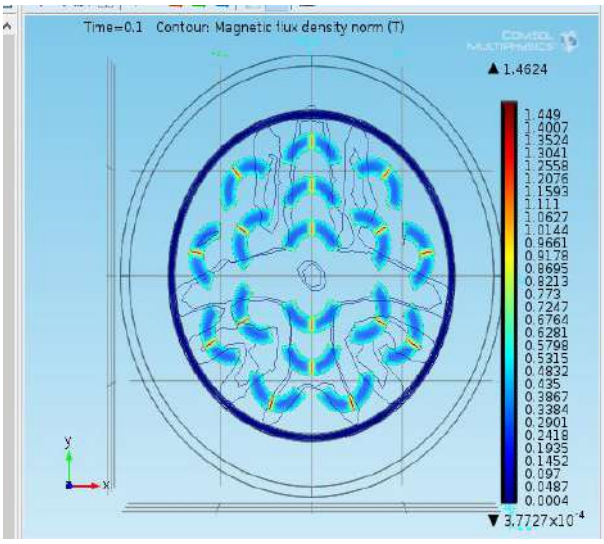
Figure III.17proposed model of eddy current separator

Figure III.17-b shows the refine mesh for another shape of the separator (vertical magnetic disk with elliptical-shaped permanent magnets and air) to obtain the highest possible accuracy

Simulation results for a second type of separator (elliptical-shaped) with permanent magnets of different polarity are shown in Figure III.18. The magnetic distribution lines around the device represent the interaction between the poles of permanent magnets, and they have been numerically studied using the finite element method.



A- Magnetic scalar potential A produced around drum (Wb/m)



B- Magnetic flux density norm (T)

Figure III.18 Magnetic characteristics of separators

The eddy-current separator is composed by number pairs of permanent magnet oriented alternately N-S and S-N respectively, will be simulate in 3D by COMSOL Multiphysics with finite element method to represent magnetic propriety of separator, the variable field of the rotating disk see Figure III.18A.

This magnetic flux density represented by Figure III.18B show the magnetic interaction between several permanent magnet and distribution around separator, the aim is to generate accurate real computation results.

As shown in the figure III.19 the varied waveform and shape, as well as the magnitude, of the magnetic flux density change in central axes for the design. The geometries and amount of permanent magnets generate these variances.

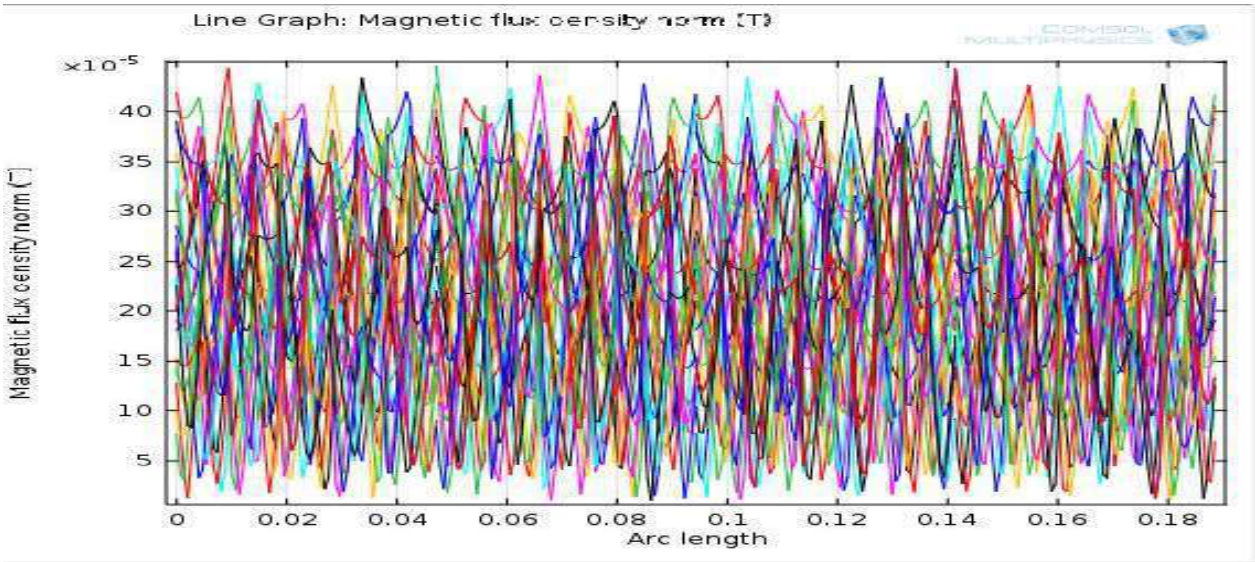


Figure III.19 Variation of the magnetic flux density according to central distance for configuration

From figure III.19 the variation of magnetic flux density measurement in diameter of magnetic disk characterized by altering magnetic field with different variation of frequencies responsible for the separation process.

III-12. Conclusion:

In this chapter, we have presented the different steps of COMSOL exploitation. The latter can be used to solve partial differential equations (PDEs), using the 3D and 2D finite element method. This method can be run boldly in a graphical user interface, which can be used to define certain data such as domain, boundary conditions, and network architecture. We also studied two different types of vertical separators, we used two different shapes of magnets:(a circular magnet and an elliptical magnet) to see the effect of the shape on variation in the distribution of magnetic field lines and also the speed of particles expelled. The presence of ferrous particles has a great influence on the physical parameters of magnetism such as field and induction, and The shape of permanent magnet plays an important role in the distribution of magnetic lines

General conclusion

Electromagnetic separation is simple and an effective technology of recovering the metallic materials from waste mixture. The eddy current separation technology 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).

We have presented the different steps of COMSOL exploitation. The latter can be used to solve partial differential equations (PDEs). The present work shows the numerical model of vertical disk of eddy current separator implementation in Comsol 4.3 Multiphysics software based on finite element method to compute the many parameters of device.

The simulate results illustrate the magnetic flux density distribution and magnitude near the separator produced by the permanent magnets in stationary and rotational states in two dimensions. The presence of non-ferrous particles around the eddy current separator conduct to induced current and ejective force on this particle is shown in the chapter III.

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.

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Abstract:

Magnetic separation is an effective technique for recovery metallic materials from mixture wastes. In this work, we modeled and simulate the magnetic characteristics of rotational disk of eddy current separator composed by several permanents magnets in two and three dimensions. The simulation model is implemented in COMSOL multiphysics software based on finite element method, the simulation results show the magnetic flux density and induced current in non-ferrous particle near the separation device.

Keywords— COMSOL, Magnetic separation, finite element method, eddy current.

Résumé :

La séparation magnétique est une technique efficace pour récupérer les matériaux métalliques des déchets de mélange. Dans ce travail, nous avons modélisé et simulé les caractéristiques magnétiques du disque rotatif d'un séparateur à courants de Foucault composé de plusieurs aimants permanents en deux et trois dimensions. Le modèle de simulation est implémenté dans le logiciel multiphysique COMSOL basé sur la méthode des éléments finis, les résultats de la simulation montrent la densité de flux magnétique et le courant induit dans les particules non ferreuses à proximité du dispositif de séparation.

Mots clés— COMSOL, Séparation magnétique, méthode des éléments finis, courants de Foucault.

خلاصة:

الفصل المغناطيسي هو تقنية فعالة لاستعادة المواد المعدنية من خليط النفايات. في هذا العمل، قمنا بنمذجة ومحاكاة الخصائص المغناطيسية للقرص الدوراني لفاصل التيار الدوامي المكون من عدة مغناطيسات دائمة في بعدين وثلاثة أبعاد. تم تنفيذ نموذج المحاكاة في برنامج COMSOL متعدد الفيزياء بناءً على طريقة العناصر المحدودة، وتظهر نتائج المحاكاة كثافة التدفق المغناطيسي والتيار المستحث في الجسيمات غير الحديدية بالقرب من جهاز الفصل.

الكلمات المفتاحية :-لفصل المغناطيسي، طريقة العناصر المحدودة، التيارات الدوامة Comsol