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Method to evaluate and prove-the-concept of magnetic separation and/or classification of particles

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ABSTRACT

When designing new magnetic separators and/or classifiers or optimizing existing ones, it is usual to face several obstacles: the high cost of a proof of concept full laboratorial setup (including preliminary optimization procedures and/or feasibility demonstrations), time-consuming experiments, lack of flexibility of the assembled laboratorial apparatus, feed complexity, among others. In this work a method and corresponding methodology are proposed to apply in such cases, representing a low-cost, flexible and robust alternative to overcome the mentioned obstacles, from which working parameters of a laboratorial or even larger version of the device may be extrapolated. This represents a powerful tool when designing magnetic separators. In the proposed methodology by determining in one experiment the magnetic force required to separate/classify a particle in a certain point, it may be derived immediately the change in magnitude and shape of the magnetic force index (**B**∇**B**) that must exist to separate other particles (with the same or different magnetic susceptibility) in another point, and it is possible to estimate, for example, the optimum, maximum or minimum value of other variables affecting the competing forces (e.g. radius of the particles, fluid density, rotation velocity), and also determine the critical limits of separation by extrapolating and obtaining the magnetic force required in those limits. It represents an open field allowing determining freely the values of the main variables. This methodology and associated method also allow repeating quickly and easily the experiments with different sets of geometrical design and positions.

A case study was analyzed and tested for both processes: magnetic separation and magnetic classification, with good results, that allowed to conclude about the feasibility of the system for both processes, and to determine the best configuration geometry.

The main objective of the present study was to demonstrate a cheap method and corresponding methodology that may be applied when designing magnetic separators and/or classifiers.

1. Introduction

Magnetic separation is a long-established method for the purification/removal of substances from fluids [1–7], mainly in mining processing industries [8,9]. In the last two decades, high developments were witnessed in application of magnetic separation to biomedical and biological downstream processing applications, mainly due to the development of nanomagnetic functionalized particles [10–16]. Other new applications, like environmental remediation and improvement in chemical processing technologies have also emerged in this century [17]. However, although many different devices have been "proposed" only some of these were developed and even fewer applied commercially. Important obstacles have been: time and money spent in preliminary tests; large spectrum of variables that play a role in the process and need to be optimized; feed complexity, among others. In fact, after designing new magnetic separators, a laboratorial-scale set of experiments with the proposed devices is always required.

Nowadays there is no established method/methodology/protocol to optimize or test a Proof-of Concept (POC) magnetic separator (or classifier). In fact when intended to test a POC of a magnetic separator/

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classifier, a full version of the preliminary design of the device must be constructed and tested, usually with very low flexibility [18–20]. When optimization of the main variables or even of the "design" is in order:

a) only a limited adaptation (of only a specific sector [21] or a specific characteristic) of the device is done (e.g. in [22] a optimized buffer-HGMS is used by manipulating the density of the fluid),
b) or modifications done in previous experimental results must be collected (e.g. in [23] it is described the collection of several experimental results obtained by different configurations and practical experiences through the years in wet drum magnetic separators)
c) or an intensive setup of experiences must be followed (e.g. in [24] in order to optimize the performance of a RER Magnetic Separator for silica sands, for only two parameters - belt speed and splitter angle of inclination - a full set of intensive experiments had to be performed, followed by statistical analysis, and in [25] intensive and long testing of feed solids concentration, drum rotational speed, position of the concentrate weir, and the magnet assembly angle was allied with modeling and measurements in order to optimize a Wet Low-Intensity Magnetic Separator, with different designs required to be tested)
d) or invariably we fall into simulation analysis (as e.g. advanced HGMS [26], HGMS by using CFD [27], HGMS Matrix filter by optimizing the behavior of filters mainly by CFD analysis [21], modeling of wet low-intensity magnetic separation [25], optimization of a magnetic separator for turbulent flowing liquid purifying applications by simulations and modeling [28]).

This work tries to overcome such a limitation by detailing a new "indirect" processing method and methodology for wet media, which allows to foresee and optimize many of the important issues and parameters (the operability and feasibility of the new device, the geometrical optimum values, positioning characteristics of the several components of the system, optimum and required magnetic field configurations, particles sizes, etc.) and perform proofs-of-concept without having to construct the full device. Furthermore it does not involve the future complex feed to be used, but by using the equivalent complexity in magnetic field configuration and by applying "mili" or microfluidics allows to simplify the feed, using commercially available magnetic particles, without affecting the conclusions to be reached. The overall system is also cheap to construct (between 5000 and 10,000 Euros) and operate.

2. Theoretical background

Magnetic separation may be described as a result of a balance of forces, which determines the resulting trajectories of the particles. The deflection of the particles from the main stream is achieved if the magnetic force acts differently and has a dominating magnitude over all the other acting forces- see Fig. 1 ([29]). As this force depends, among other factors, on the magnetic characteristics of the particles (see Eq. (1)), the deflection is more pronounced in the more magnetic, less pronounced on the weakly magnetic and apparently does not affect the very weakly magnetic particles.

The forces involved in the majority of the magnetic separating systems are described, for example, in [9,10,17,30].

The magnetic force ($\mathbf{F_m}$) (the driving force on magnetic separation) in a paramagnetic and small ferromagnetic particle is given by:

$$\mathbf{F_m} = \frac{m\chi}{\mu_0}\mathbf{B}\nabla\mathbf{B} \tag{1}$$

Being m the mass of the particle, χ its magnetic susceptibility and μ_O is the magnetic permeability of vacuum. $\mathbf{B}\nabla\mathbf{B}$ is the *magnetic force index* ([31]), defined as

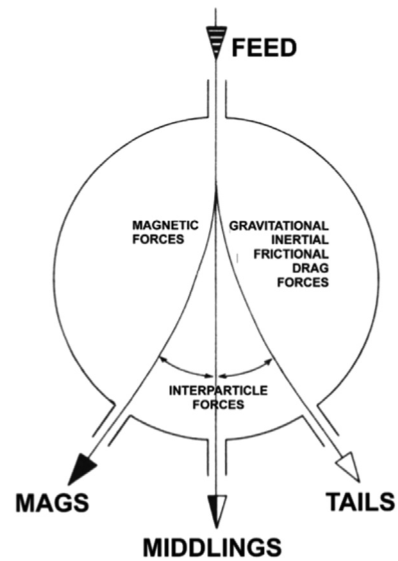

Fig. 1. Schematic representation of a Magnetic Separation Process (based on [8,29]).

$$\mathbf{B}\nabla\mathbf{B} = \left(B_x\frac{\partial B_x}{\partial x} + B_y\frac{\partial B_y}{\partial x} + B_z\frac{\partial B_z}{\partial x}\right)\mathbf{i} + \left(B_x\frac{\partial B_x}{\partial y} + B_y\frac{\partial B_y}{\partial y} + B_z\frac{\partial B_z}{\partial y}\right)\mathbf{j} + \left(B_x\frac{\partial B_x}{\partial z} + B_y\frac{\partial B_y}{\partial z} + B_z\frac{\partial B_z}{\partial z}\right)\mathbf{k} \tag{2}$$

where B_x, B_y, B_z are the magnetic field magnitudes components in each coordinate.

2.1. Magnetic Separation

The separation described in Fig. 1 occurs if particles follow the necessary, but not sufficient, conditions that the magnetic force acting on the strong magnetic particles - F_{mag}^{m} - are higher than the sum of the competing forces - F_e^{im} -, and that the magnetic force acting on the very week magnetic particles - F_{mag}^{n} - are lower than the sum of the competing forces - F_e^{in} -, meaning [4]):

$$F_{mag}^{m} \geq \sum_i F_e^{im} \tag{3}$$

$$F_{mag}^{n} \leq \sum_i F_e^{in} \tag{4}$$

Inequality (3) applies to strong magnetic particles, while inequality (4) is usually used for the remaining magnetic particles of the system.

From the previous two inequalities it may be also concluded that for a separation between strong magnetic particles and other magnetic particles to be achieved in a certain device, in a certain point, the following criteria should be observed:

$$\frac{F_{mag}^{m}}{F_{mag}^{n}} \geq \frac{\sum_i F_e^{im}}{\sum_i F_e^{in}} \tag{5}$$

Therefore, inequality (5) constitutes the minimum critical limit between separable and non-separable particles, on a specific position.

In the majority of practical magnetic separators it may be assumed that the sum of the competing forces is the same for every particle (in order to achieve a separation based on magnetic characteristics and not on other particle characteristic) or its magnitude is some orders of magnitude lower than the acting magnetic forces. Therefore, in such a case, inequality (5), turns-out into:

$$\frac{F_{mag}^{m}}{F_{mag}^{n}} \geq 1 \tag{6}$$

For small paramagnetic, diamagnetic or ferromagnetic particles,