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A continuum based numerical modelling approach for the simulation of WHIMS

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ABSTRACT

Wet high intensity magnetic separators are used in magnetic separation of minerals with low susceptibility. The dynamic process of material built-up in the matrix is influenced, among others, by the matrix geometry, gradient and strength of the magnetic field. These factors, however, do change with the built-up of magnetic material in the matrix.

Detecting the built-up of magnetic material is crucial to the continuous operation of the separation process. In this study we present a numerical modelling approach for wet high intensity magnetic separation. The electromagnetic and the fluid flow field are modelled with the finite element method, while the material particles are identified and evolved using the Level-set approach. Such a framework retains the influence of magnetic particles on the surrounding magnetic field and can be used to detect and predict material build-up in the matrix. The model is validated with a benchmark example and the potential of the approach is demonstrated using a simplified magnetic separation matrix example.

1. Introduction

The beneficiation of valuable minerals, such as tungsten (W) and tantalum (Ta), typically involves a series of separation processes. Through these processes, the grade and quality of the valuable mineral is gradually increased from a low-grade raw-ore concentration to a high-grade final product. The application and success of a particular separation process is strongly dependent on the composition and characteristics of the feed material, the intended product and the gangue minerals. Most common separation technologies for these materials can be broadly categorized into three groups: gravity separation, flotation and magnetic separation. In this article, we present a computational modelling approach for simulating a magnetic separation process, typically employed in the beneficiation of W and Ta minerals.

Commercially, W and Ta are often extracted from pegmatite-type rock deposits, which are composed of several mineral groups. Among these groups, wolframite $(Fe,Mn)WO_4$ is the chief source of W, while Ta is mainly contained in the columbite-tantalite $(Fe,Mn)(Nb,Ta)_2O_6$ mineral group. The presence of these mineral groups in the mined rock deposits is generally of low-grade nature and therefore the ore must be significantly comminuted to liberate the minerals prior to a separation process, resulting in very fine feed particles. Additionally, wolframite and columbite-tantalite (coltan) are generally characterized as weakly ferromagnetic minerals, with a mass susceptibility range of 0.3×10^{-6}–$1.2 \times 10^{-6}\ m^3\ kg^{-1}$ and 22.1×10^{-6}–$37.2 \times 10^{-6}\ m^3\ kg^{-1}$, respectively. Due to the weak magnetic response of these minerals – further diminished by the fine size of mineral particles – low and moderate intensity magnetic separation processes are not suitable for the beneficiation of such minerals and instead wet high intensity magnetic separators (WHIMS) find prevalent industrial usage.

Also referred as the high gradient magnetic separator (HGMS), a WHIMS employs a matrix, which acts as a magnetized filter when exposed to an external magnetic field. The surface topology of the matrix is intentionally kept irregular (e.g., with sharp regular asperities, wires, etc.) to have an irregular magnetic field with localized field gradients within the matrix. When the feed material flows through the matrix, the gradients in the magnetic field produce a force imbalance on the magnetic particles in the feed, forcing them to move towards the surface of the matrix and ultimately getting deposited there. The nonmagnetic particles pass through the matrix unhindered. Once the feed is stopped, the magnetic field is removed and the matrix is rinsed to collect the magnetic material. In a batch operation, the matrices are placed in a rotating disc arrangement which moves them continuously between regular magnetization and rinse cycles. The Jones separator is a well known example of a WHIMS.

Although some experimentally motivated mathematical models such as Corrans and Levin (1979), Tucker (1994), and Liu et al. (2008) exist in literature for WHIMS, their application remains restricted to the

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estimation of mineral recovery as a function of various process parameters. A detailed representation and understanding of the underlying physical process remains outside the scope of such models. A typical WHIMS involves multiple interacting physical phenomena, among which electro-magnetism, fluid dynamics, particle kinetics and multi-body contact are the dominant ones. Therefore computational modelling approaches in a coupled-field framework are increasingly being adopted for the detailed analysis of WHIMS. In Okada et al. (2005), the authors propose a computational fluid dynamics (CFD) based approach for modelling the fluid flow and the magnetic field to estimate the deposition of magnetic particles on magnetized wires. The magnetic field is considered steady and the influence of accumulating particles on the underlying magnetic and flow field is not considered. Another CFD based approach that uses the volume of fluid (VOF) method to estimate the distribution of magnetic and non-magnetic particles in a triangular matrix is presented in Mohanty et al. (2011). The magnetic field, though is obtained analytically by modelling the magnetic plates with a series of magnetic dipoles. The boundary element method (BEM) for CFD analysis coupled with an analytically obtained magnetic field and a Lagrangian particle tracking approach, as shown in Ravnik and Hriberšek (2013), offers a computationally less expensive approach for modelling magnetic separation processes. However, its application is restricted to laminar flow problems with simple geometries. An effort to numerically solve most of the dominant fields involved in HGMS is summarized in Lindner et al. (2013). Here, the discrete element method (DEM) is employed to identify and determine individual particle trajectories in a fluid and a magnetic field, which are modelled through CFD and finite element method (FEM), respectively. A similar framework was also employed for modelling a low intensity magnetic separator (LIMS) in Murariu (2013). DEM provides an accurate representation of individual particles and a framework for including inter-particle dynamics. However, the dynamic behavior of the underlying magnetic field due to increasing particle accumulation is not retained in the simulation since the magnetic field is determined considering a domain without particles.

In this article, we present a novel computational modelling framework that inherently retains the ability to model the influence of magnetized particles on the surrounding magnetic field. We feel that such a description is necessitated to accurately model and understand the often encountered operational difficulty of matrix blockage in an industrial WHIMS (Corrans and Levin, 1979). In a magnetic field, magnetized particles tend to accumulate on top of each other and an excessive buildup leads to the choking of the matrix, which consequently leads to a short-circuited magnetic field. The separation efficiency of a clogged matrix is significantly low and the entire process suffers until the matrix is properly rinsed. Such a handicap can effectively be identified and rectified at the matrix design stage through detailed computational simulations corresponding to the operating conditions. Additionally, a model that adequately reflects the separation dynamics of a WHIMS can be implemented in the machine and the process control to prevent losses in product, as well as in process efficiency.

To simulate the variations experienced by an otherwise steady magnetic field in a WHIMS matrix due to the presence of magnetic particles, we propose an entirely continuum based representation of all the involved fields. In this context, the electro-magnetic field is obtained through the numerical solution of the Maxwell's equations expressed in the form of a magnetic vector potential, while the particle geometry and movement is identified using the interface capturing level set approach. The entire continuum is discretized with finite elements. To effectively capture the jumps in the magnetic fluxes across different interfaces (matrix-air, matrix-water, water-particle), we have adopted the edge finite elements to solve the Maxwell's equations. It is further envisaged that the proposed formulation will be coupled with a stabilized nodal finite element fluid flow solver (Brooks and Hughes, 1982; Hughes and Mallet, 1986; Hansbo and Szepessy, 1990) in future for flow field modelling. The proposed approach offers a novel framework that can be easily extended to simulate and analyze the matrix blockage phenomenon in WHIMS.

The remainder of this paper is organized in the following manner: the mathematical framework for the proposed approach is laid out in Section 2. This includes the governing differential equations expressed in their strong and weak forms. Firstly, the governing equation for modelling the magnetic field is introduced. This is followed by the level set framework for particle identification and evolution. Using the determined magnetic field and the identified particle representation, the trajectory of the mineral particle is determined using the net resultant force acting on the mineral particle. Results and observations based on two numerical examples are discussed in Section 3. Finally, conclusions are drawn in Section 4.

2. Continuum-based model

The mathematical framework for the continuum based approach is summarized in this section. At the moment, two dominant fields are considered. These include the magnetic field generated by an electric current source and the magnetic particles that occupy the matrix cavity.

2.1. The magnetic field

The standard approach to numerically obtain a magnetic field is to solve the Maxwell's equations. In this regard, let us consider a region comprising of two contiguous bodies $\mathscr{B}_1$ and $\mathscr{B}_2$ with permeabilities μ_i, where $i = 1,2$. An extension to multiple contiguous bodies is trivial. The static magnetic field within these media generated due to a source current density $\boldsymbol{J}_0$ is governed by the Maxwell's equations of the form:

$$\nabla \times \boldsymbol{H}_i = \boldsymbol{J}_0 , \quad \forall \ \boldsymbol{x} \in \mathscr{B}_i, \tag{1}$$

$$\nabla \cdot \boldsymbol{B}_i = 0 , \quad \forall \ \boldsymbol{x} \in \mathscr{B}_i. \tag{2}$$

Here, $\boldsymbol{H}_i$ is the magnetic field intensity and $\boldsymbol{B}_i$ is the magnetic flux density in the body $\mathscr{B}_i$. $\boldsymbol{x}$ represents a point where the magnetic field is evaluated. The operation $\nabla \times \boldsymbol{u}$ and $\nabla \cdot \boldsymbol{u}$ represents the curl and divergence operations, which for an arbitrary three-dimensional vector $\boldsymbol{u} = (u_x, u_y, u_z)$ are defined as

$$\nabla \times \boldsymbol{u} = \left(\frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z}\right)\boldsymbol{e}_x + \left(\frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x}\right)\boldsymbol{e}_y + \left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right)\boldsymbol{e}_z, \tag{3}$$

$$\nabla \cdot \boldsymbol{u} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}. \tag{4}$$

For a magnetically linear material, the magnetic field intensity and the magnetic flux density are related by the following constitutive relation:

$$\boldsymbol{B}_i = \mu_i \boldsymbol{H}_i. \tag{5}$$

It is pertinent to mention that μ_i is related to the volume magnetic susceptibility χ_i through the relation $\mu_i = \mu_0(1 + \chi_i)$, where μ_0 is the permeability of vacuum. At the interface where the two bodies meet, the continuity of normal component of $\boldsymbol{B}_i$ and the tangential component of $\boldsymbol{H}_i$ should be ensured, i.e,

$$\left.\begin{aligned} \boldsymbol{B}_1 \cdot \boldsymbol{n}_1 + \boldsymbol{B}_2 \cdot \boldsymbol{n}_2 = 0, \\ \boldsymbol{H}_1 \times \boldsymbol{n}_1 + \boldsymbol{H}_2 \times \boldsymbol{n}_2 = 0, \end{aligned}\right\} \quad \forall \ \boldsymbol{x} \in \partial\mathscr{B}_1 \cap \partial\mathscr{B}_2, \tag{6}$$