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Particle capture modeling for an axial magnetic filter with a bounded non-Newtonian flow field

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ABSTRACT

Capturing fine magnetic particles in axial magnetic filter from non-Newtonian suspension was examined theoretically. A trajectory model was formed for the movement of the particle in bounded flow field magnetic filter that has advantages for various theoretical modeling and practical applications as presented in the literature [1–8]. The effects of the non-Newtonian properties of the suspension on the particle capture distance were evaluated. Since the magnetized ferromagnetic wire was outside the cylindrical tube in which the suspensions flow, the velocity profile within the tube was determined according to the power law rheological model. The conditions to use the approximation expression for the flow profile in the tube were determined by considering the energy dissipation. Analytical solutions for the particle trajectory equation were obtained under above-mentioned conditions. Based on these results, the effects of the non-Newtonian properties of the carrier suspension on the movement trajectory of the particle and the capture cross-section were scrutinized.

1. Introduction

The method of high-gradient magnetic filtration (HGMF) is a physical method used to separate the micron-size magnetic particles that suspensions contain. The methods of separation or enrichment of magnetic particles from other media are contemporary to Thomas Edison. However, from 1960 to 70's on, the theory and the practice of separation or filtration of the particles in high-gradient magnetic fields formed by ferromagnetic material (wire, sphere, chips, steel wools) that magnetize in exterior magnetic field have developed rapidly. These methods initially used in the process of separation of minerals [9–13], were used effectively to resolve environmental problems using physical methods [14–17], and in medical and biological processes [18–23] later on. Recently, separation and filtration theory and practice have developed to provide effective applications and results in micro and nanotechnology systems via magnetophoresis processes [18,19]. High-yield application findings in several fields were also reported in high-gradient magnetic fields literature [24,25]. The basis of high-gradient magnetic filtration or separation method is the capture of the particles on the ferromagnetic element magnetized by the external magnetic field that flows perpendicular to the symmetry axis. Spheres, wires, chips, plaques, steel wools, etc. could be used as ferromagnetic elements. Axial-type HGMF, which has both theoretical and practical advantages, was examined more prevalently [26–28]. In axial-type HGMF, although the external magnetic field is perpendicular to the ferromagnetic wire, the flow direction of the suspension that carries the particle is parallel to the wire. Capture of the particles on magnetized wire in axial-type HGMF was investigated under potential [13] and laminar [26,27] flow conditions of the carrier suspension. Also the effects of the rheological properties (power law flow model) of the carrier suspension in capturing of the particles were scrutinized [29]. In all models mentioned above, magnetized ferromagnetic wire is in direct contact with cleaned suspension. However, several serious issues arise under these conditions in practical applications of HGMF, especially in corrosion-preventive cleaning processes in aggressive media. To resolve these issues, a HGMF model that provides cleaning without the contact of ferromagnetic wire and the suspension was presented and was analyzed theoretically and empirically in the literature [1–8]. In this filter model, the cleaned suspension flows in a tube. Magnetized ferromagnetic wire is located outside the tube and parallel to the flow of the suspension [Fig. 1].

Theoretical and empirical trials with this type of HGMF [1–8] that has significant practical advantages were basically conducted for Newtonian suspensions. However in practice, under several conditions, cleaned suspensions often demonstrate rheological properties since they contain various organic and inorganic mixtures.

Whether the carrier suspensions are weakly non-Newtonian or highly non-Newtonian rheological properties, in all cases by HGMF can have weak or effective non-Newtonian properties. However, HGMF characteristics have different properties. Therefore the methods presented in the literature [1–8] are inadequate to explain these events.

This study examines the capture of small particles in non-Newtonian suspension using an axial-type HGMF theoretically. The flow-velocity profile of the suspension in cylindrical tube was determined according to power low model, and by taking the expression of drag force into

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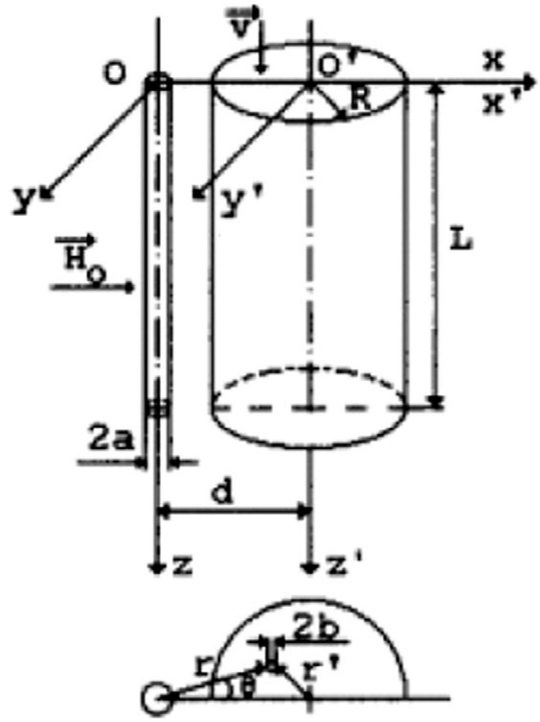

Fig. 1. Schematic diagram of the system analyzed [1].

consideration, a trajectory model for the particle in non-Newtonian suspension was created. By taking the energy dissipation in non-Newtonian fluid flow, the limits of the approximate solution for the motion equation of the particle were determined, and the approximate solution for the motion equation of the particle for weak non-Newtonian fluids was obtained. The effects of non-Newtonian properties of the cleaned suspension on the capture length and capture cross-section arc were evaluated.

2. Formulation of the problem and trajectory equations

For the analysis of the magnetic particle motion, the system developed by N. Rezlescu et al. and displayed in Fig. 1 was selected as the starting point [1].

According to Fig. 1, The cylindrical ferromagnetic wire of radius a, length L and saturation magnetization M_s is fixed along the Oz axis and magnetized to saturation by an external magnetic field with the intensity H_0, applied along the Ox axis. The cylindrical tube with inner radius R and length L, is fixed along Oz axis, coplanar with the Oz axis in the plane $y = 0$, at a distance d.

A spherical paramagnetic particle with radius b and magnetic susceptibility χ_p is carried by a fluid with magnetic susceptibility χ_f. It was assumed that the fluid that carried the particle had a weakly non-Newtonian properties ($|n - 1| \ll 1$) and its rheological properties were determined by Ostwald De Wiale (power law) model where non-Newtonian behavior is n [30]. The balance of forces which describes the particle motion is given by

$$\overline{F}_i = \overline{F}_m + \overline{F}_g + \overline{F}_d \tag{1}$$

where $\overline{F}_i$ is the inertial force, $\overline{F}_m$ is the magnetic force, $\overline{F}_g$ is the buoyant force and $\overline{F}_d$ is the hydrodynamic force, all acting on the particle. We consider the particle small enough to neglect its weight and inertia. Under the circumstances, the motion trajectory of the particle would be determined as a result of the competition of the main two forces, magnetic ($\overline{F}_m$) and hydrodynamic drag $\overline{F}_d$.

$$\overline{F}_m + \overline{F}_d = 0 \tag{2}$$

The open expressions of forces contained in Eq. (2) are determined as follows. The magnetic force is given by

$$\overline{F} = V_p (\overline{M}_p . \nabla) \overline{H} \tag{3}$$

where $\overline{H}$ is the magnetic field intensity, $\overline{M}_p$ is the magnetization of the particle, V_p is particle volume ($= 4\pi \times b^3/3$). The magnetic force exerted on the particle has the following components expressed in the cylindrical coordinates (r, θ, z) [1];

$$F_{\mathrm{Mr}} = -\mu_0 V_p \chi M_s a^2 \left(\frac{M_s a^2}{r^5} + \frac{H_0}{r^3} \cos 2\theta \right) \tag{4 – a}$$

$$F_{\mathrm{M\theta}} = -\mu_0 V_p \chi M_s a^2 \frac{H_0}{r^3} \sin 2\theta \tag{4 – b}$$

$$F_{\mathrm{Mz}} = 0 \tag{4 – c}$$

where $\chi = \chi_p - \chi_f$, and μ_0 is magnetic constant ($= 4\pi \times 10^{-7}$H/m)). Non-Newtonian properties of the particle carrier medium cause changes both in hydrodynamic drag force and the flow profile. Thus, it is necessary to further mention the determination of the hydrodynamic drag force that affects the particle in non-Newtonian fluids. Drag force that generally affects small particles in non-Newtonian fluids occurs due to several factors and in a complex manner [31]. However, considering the properties of the problem investigated, these expressions could be rewritten in a more comprehensive and useful way. In this section, approximate expressions would be obtained for the non-Newtonian fluid flow regime and the drag force that affects the particle.

2.1. Determination of approximate expressions of flow velocity regime and drag force acting on the particles in tube for the non-Newtonian fluid

Generally, the velocity gradient in radial direction in non-Newtonian (power law) fluid flow in a cylindrical tube with a radius of R is determined as follows [30],

$$-\frac{dV_z}{dr'} = \left(-\frac{r'}{2K} \cdot \frac{dP}{dz} \right)^{\frac{1}{n}} \tag{5}$$

where r' is radial coordinate from center of tube, K is consistence coefficient, and $\frac{dP}{dz}$ is pressure drop.

When limiting conditions are taken into consideration, the flow-velocity profile of the fluid based on power law model in a cylindrical tube with a radius of R is determined as follows:

$$V_z = \frac{3n+1}{n+1} V_{av} \left[1 - \left(\frac{r'}{R} \right)^{\frac{n+1}{n}} \right] \tag{6}$$

where $V_{av} = \frac{Q}{\pi R^2}$ is the average velocity of fluid and Q is the flow rate of fluid.

From Fig. 1, $(r')^2 = r^2 + d^2 - 2rd \cos\theta$. In that case,

$$\left[\left(\frac{r'}{a} \right) \right]^{\frac{n+1}{n}} = \left[\left(\frac{r}{a} \right)^2 + \left(\frac{d}{a} \right)^2 - 2 \left(\frac{r}{a} \right) \left(\frac{d}{a} \right) \cos\theta \right]^{\frac{n+1}{2n}} \tag{7}$$

Eqs. (7), (6), and (4-a),(4-b),(4-c) could be used to create the trajectory equation for the particle in (z, t) coordinates. When the fluid