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Sedimentation dynamics of ferrofluid droplets under magnetic field

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Abstract. Understanding the controlled manipulation of droplet dynamics in multiphase systems is crucial for improving oil-water separation processes in the petroleum industry. The application of external magnetic fields to ferrofluid droplets offers a promising strategy for enhancing phase segregation in magnetic emulsions. This study presents a numerical investigation of the sedimentation behavior of a single ferrofluid droplet due to gravity, subjected to uniform magnetic fields applied in horizontal or vertical orientations. A magnetohydrodynamic (MHD) model was developed and implemented in the Basilisk open-source framework, using direct numerical simulation (DNS). The software resolves variable density and viscosity fields with second-order accuracy in time and space and employs the Bell–Colella–Glaz second-order upwind scheme for velocity advection. Interface dynamics were captured with the Volume of Fluid (VoF) method, incorporating balanced continuous surface force formulation for surface tension and magnetic forces through the Kelvin force. The simulations reveal that magnetic field orientation critically affects droplet deformation and terminal velocity. The magnetic effects intensify with reduced surface tension. These results provide insights into magnetic control strategies for optimizing droplet separation processes in petroleum engineering applications involving ferrofluid emulsions.

Keywords: droplet dynamics, magnetic field, ferrofluid droplets, direct numerical simulation, magnetohydrodynamics.

1 Introduction

Droplet dynamics plays a fundamental role across various petroleum industry operations, from recovery and transport to primary processing, where applications may target viscosity reduction in flow or maximization of separation efficiency during processing. The literature demonstrates that magnetic field application can induce phase separation in immiscible liquids through several underlying physical mechanisms, including magnetic energy interactions, magnetic thermoelectric convection, and interfacial force modulation.

Recent investigations have examined how magnetic field orientation affects ferrofluid droplet behavior in different flow configurations. Guilherme et al. [1] studied ferrofluid droplets in planar extensional flows using Level Set methodology, demonstrating that magnetic field direction significantly influences droplet deformation and revealing novel rheological signatures. Their work showed that droplet shape transitions under magnetic fields depend on both field direction and the magnetic capillary number, with specific orientations leading to distinct

cross-sectional geometries. They found that the interplay between magnetic forces and flow-induced stresses creates complex deformation patterns that depend critically on field orientation relative to the flow direction.

Kawabata et al. [2] employed the Boundary Integral Method to model deformation in shear flows, while Bhattacharjee et al. [3] utilized asymptotic approaches for small deformation limits, observing that high magnetic field intensity can lead to instability and droplet breakup. Yang et al. [4] studied coupled electric and magnetic field influences, showing that magnetic fields can suppress electric field-induced deformation under certain conditions.

While these studies have advanced understanding of magnetic field orientation effects in controlled flow environments, there remains limited investigation of how field orientation specifically affects droplet sedimentation dynamics in gravitational fields, a critical consideration for industrial separation processes. This study builds upon existing knowledge by investigating magnetic field interaction with inertial, viscous, and surface tension effects during free sedimentation, with particular focus on how horizontal versus vertical magnetic field orientations influence droplet drag coefficients, terminal velocities, and overall separation efficiency in petroleum processing applications.

2 Methodology

2.1 Problem Description

The computational domain consists of a 2D square with side length $S = 50D$, where D is the initial spherical droplet diameter, as illustrated in Fig. 1. The coordinate system (x,y) is positioned at the initial center of mass location. The droplet starts from rest at an initial distance $z_i = 5D$ from the domain's upper boundary. Droplet aspect ratio is given by b/a. No-slip velocity conditions and Neumann pressure conditions are applied at all boundaries. A constant, uniform magnetic field with intensity H_0 is applied in horizontal or vertical directions.

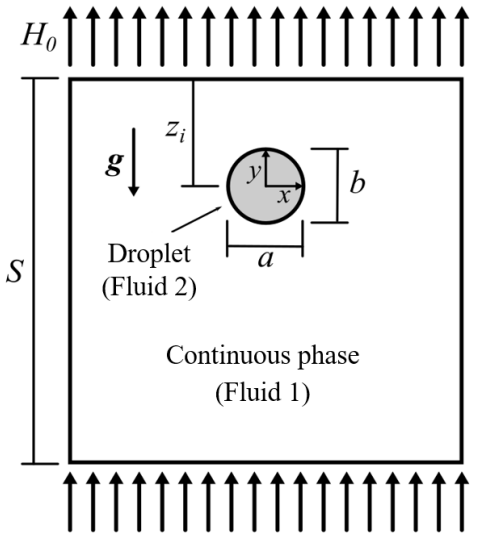


Figure 1. Schematic of the computational domain of 2D simulations

2.2 Mathematical Modeling

The mathematical modeling adopts a one-fluid approach for multiphase flow. The interface is tracked by a passive tracer advection equation f. Fluids are treated as Newtonian and incompressible, with eq. 1 mass conservation, eq. 2 momentum conservation and eq. 3 interface advection equations:

$$\mathrm{div}(\mathrm{u_j}) = 0; \tag{1}$$

$$\partial_t \mathrm{u_j} + \mathrm{div}(\mathrm{u_j} \otimes \mathrm{u_j}) = \frac{1}{\rho}\left[-\mathrm{grad(p)} + \mathrm{div}(2\mu \mathrm{D_{ij}})\right] + \mathrm{a_j}; \tag{2}$$

$$\partial_t f + u_j \cdot grad(f) = 0; \tag{3}$$

where u_j is the velocity vector, p is pressure, μ is the phase-averaged viscosity, ρ is the phase-averaged density, and D_{ij} is the deformation tensor. The acceleration term a_j includes gravitational acceleration g, surface tension acceleration $a_{\sigma,j}$, and magnetic acceleration $a_{m,j}$, with the latter two concentrated at the interface. The surface tension acceleration is given by eq. 4:

$$a_{\sigma,j} = \sigma \kappa n_j \delta_S / \rho, \tag{4}$$

where σ is the surface tension coefficient, κ is interface curvature, n_j is the unit normal vector to the interface, and δ_S is the Dirac delta function. The magnetic acceleration is given by eq. 5:

$$a_{m,j} = \mu_0 \chi H_j \cdot grad(H_j), \tag{5}$$

where μ_0 is vacuum permeability, χ is droplet material susceptibility, and H_j is the magnetic field vector. Since H_j is irrotational, $H_j = grad(\psi)$, where ψ is the magnetic potential determined by Maxwell's equation, eq. 6:

$$div\big((1+\chi)\, grad(\psi)\big) = 0. \tag{6}$$

Viscosity is given by harmonic averaging, while density is given by arithmetic averaging, both weighted by volume fraction.

2.3 Dimensionless parameters

The following dimensionless parameters characterize the problem. Arquimedes number (Ar), in eq. 7, represents the ratio of buoyant to viscous forces:

$$\mathrm{Ar} = \frac{\sqrt{\rho_1 |\Delta\rho| g D^3}}{\eta_1}, \tag{7}$$

where ρ_1 is the density of continuous phase, $\Delta\rho$ is the difference between the density of continuous phase and droplet, g is the gravity, D is the droplet diameter and η_1 is the viscosity of continuous phase.

Bond number (Bo), in eq. 8, represents the ratio between buoyancy and surface forces:

$$\mathrm{Bo} = \frac{|\Delta\rho| g D^2}{\sigma}. \tag{8}$$

Gravitational-magnetic number (Mg), in eq. 9, represents the ratio of buoyant and magnetic forces:

$$Mg = \frac{|\Delta\rho| g}{\mu_0 \chi {H_0}^2}, \tag{9}$$

where H_0 is the external magnetic field.

In the simulations, Bo and Mg assume values of 1, 5, and 25, while Ar is kept constant at 1. Other parameter values, such as the viscosity (η_1/η_2) and density (ρ_1/ρ_2) ratios, are fixed at 0.1 and 1.25, respectively.

2.4 Numerical approach

Numerical simulations were performed using the open-source Basilisk software, which employs dynamic adaptive mesh refinement and has demonstrated accuracy and efficiency in surface tension-dominated flows. The mesh adapts dynamically based on volume fraction gradients, velocity fields, and magnetic potential. Equations are discretized with second-order accuracy using the Bell-Collela-Glaz scheme on an adaptive Cartesian mesh with octree structure.

3 Results and discussion

3.1 Numerical Code Validation

Code validation reproduced the analytical solution of Afkhami et al. [5] for aspect ratios of suspended droplets under uniform magnetic fields. Mesh dependency tests, in Fig. 2(a), showed minimal variation in aspect ratio for maximum refinement levels 10 and 11, with level 10 selected for computational efficiency. Comparison with analytical predictions, in Fig. 2(b), showed good agreement with approximately 6% average error for equilibrium droplet aspect ratios as a function of magnetic Bond number (Bo_m). Figure 2(c) illustrates the mesh structure in a region near the droplet.

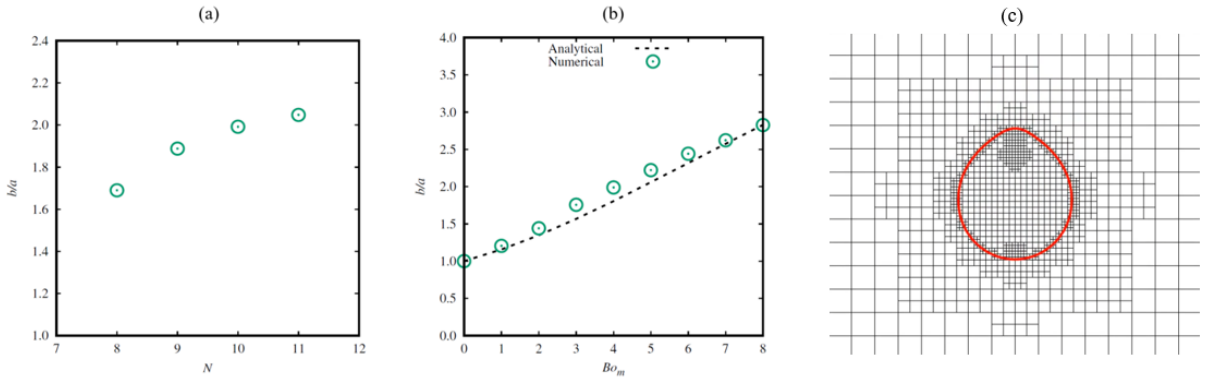


Figure 2. Aspect ratio, b/a, of ferrofluid droplets under the action of a uniform magnetic field as a function of (a) the level of mesh refinement, N, and (b) the magnetic Bond number, Bo_m; and (c) computational mesh in a portion of the simulation domain

3.2 Horizontal magnetic field effects

Figure 3(a) shows droplet aspect ratio (b/a) as a function of Mg for different Bo values under horizontal magnetic field. The aspect ratio decreases with decreasing Mg (increasing of H_0) and increasing Bo (decreasing of surface tension). In the imposed field direction, Kelvin force stretches the droplet perpendicular to gravity, reducing its aspect ratio. Increased Bo reduces surface tension effects relative to buoyancy, allowing magnetic effects to deform droplets more easily to lower aspect ratios.

This aspect ratio effect reflects in sedimentation velocity, as shown in Fig. 3(b), where terminal velocity magnitude decreases as droplet drag coefficient increases with reduced Mg and increased Bo. Consequently, horizontal magnetic fields in gravitational separators tend to reduce droplet separation rates.

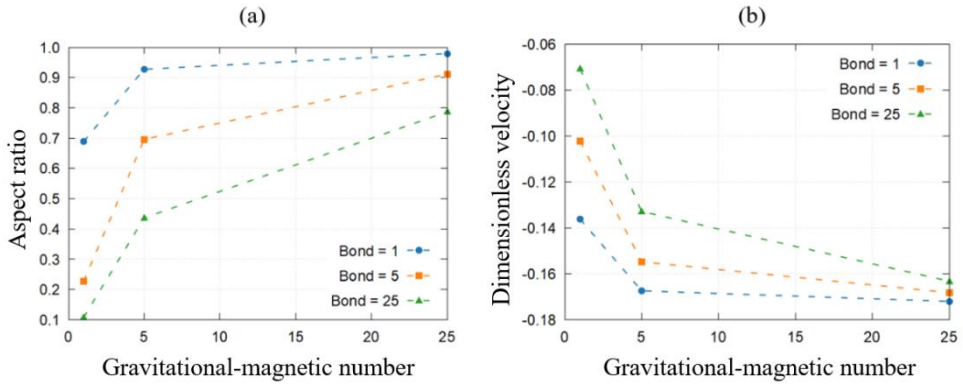


Figure 3. (a) aspect ratio and (b) droplet sedimental velocity as function of Mg for different values of Bo, with the horizontal magnetic field

3.3 Vertical magnetic field effects

Under vertical magnetic fields, Fig. 4(a) shows that the field tends to increased aspect ratio, opposite to horizontal field effects. This effect intensifies with increased Bo due to greater droplet deformability. Consequently, droplet sedimentation velocity increases, as demonstrated in Fig. 4(b), due to reduced drag coefficient, enhancing separation efficiency.

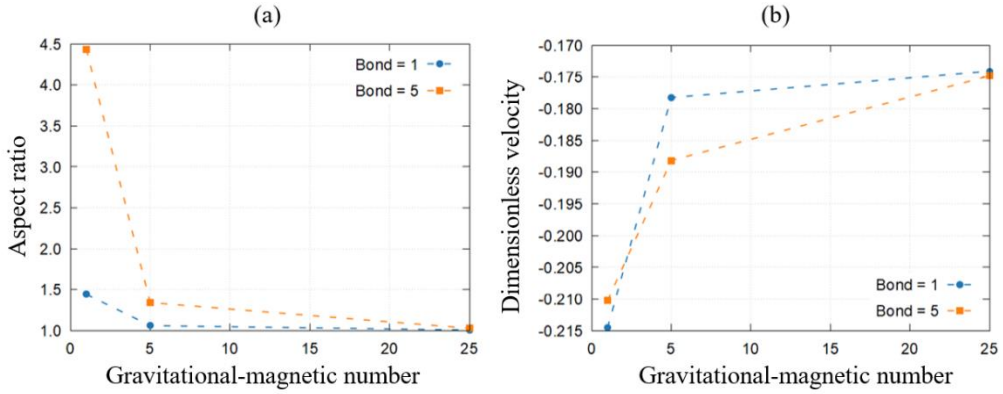


Figure 4. (a) aspect ratio and (b) droplet sedimental velocity as function of Mg for different values of Bo, with the vertical magnetic field

3.4 Practical implications

Figure 5 presents droplet shapes under horizontal and vertical magnetic field orientations. The results demonstrate that field direction has a critical influence on separation efficiency. In the horizontal configuration, as shown in Fig. 5(a), the droplet adopts an oblate shape, which reduces settling rates due to increased hydrodynamic drag. In contrast, under vertical magnetic fields, as illustrated in Fig. 5(b), the droplet tends to become prolate, promoting faster separation by minimizing drag. The intensity of these effects depends strongly on the balance between surface tension, magnetic forces, and buoyancy, as characterized by the Bond (Bo) and magnetic (Mg) numbers.

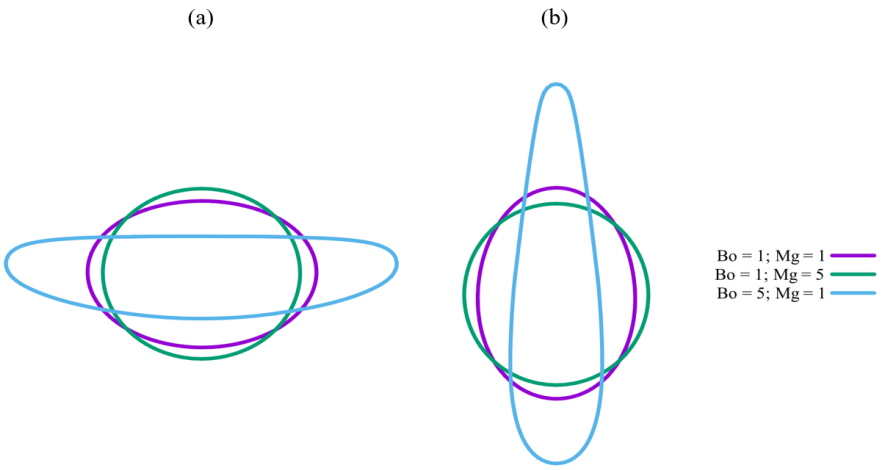


Figure 5. Droplet shapes under (a) horizontal and (b) vertical magnetic fields

4 Conclusions

This investigation examined magnetic field intensity and orientation effects on ferrofluid droplet sedimentation. Horizontal magnetic fields make droplets more oblate, increasing drag coefficient and reducing

sedimentation velocity. Vertical magnetic fields produce opposite effects, creating prolate droplets with enhanced sedimentation. Surface tension reduction intensifies magnetic effects on droplet shape.

These findings provide design guidelines for magnetic-enhanced separation systems in petroleum processing. Future work should include Lorentz magnetic force effects alongside Kelvin force and non-Newtonian fluid behavior.

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