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High-Gradient Magnetic Separation of Magnetic Nanoparticles Using Elliptical Shaped Wire

NATIONAL MAGLAB

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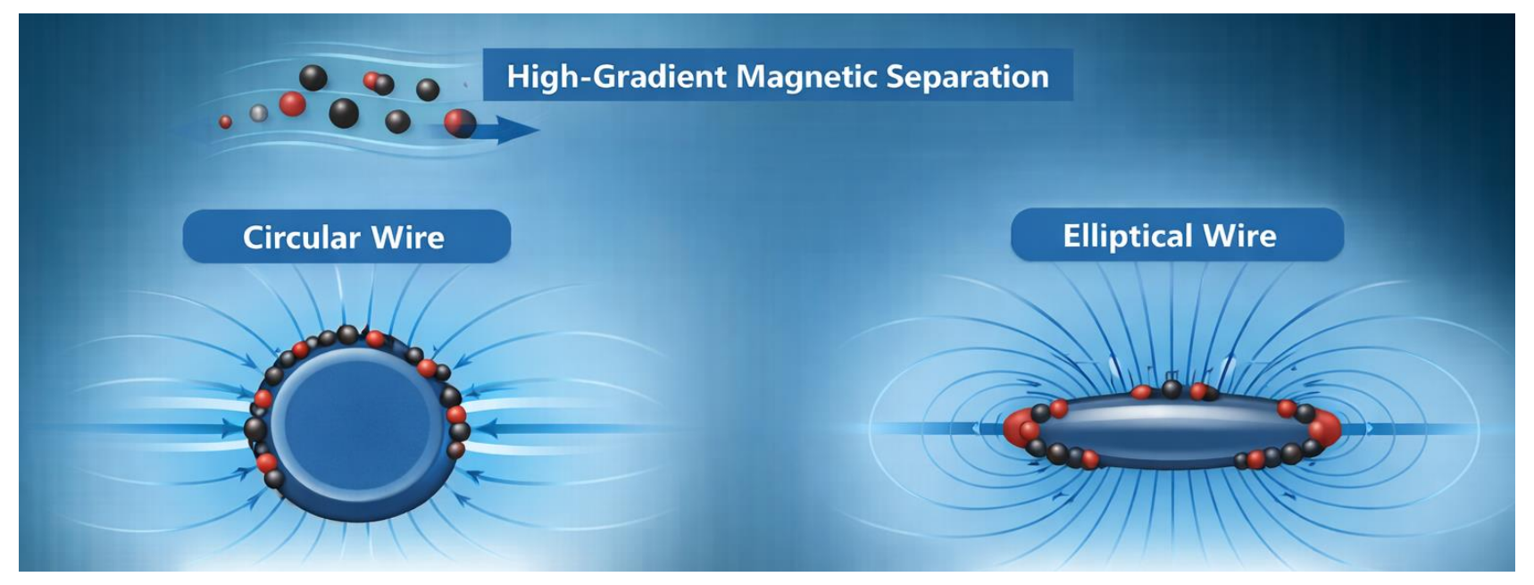
INTRODUCTION

High-gradient magnetic separation (HGMS) has emerged as a vital technique for capturing magnetic particles under the influence of strong magnetic field gradients, with applications spanning industries such as mineral processing, wastewater treatment, environmental remediation, and biotechnology.

$$F_m = \frac{4\pi\Delta\chi R_p C}{3\mu_0}(B\cdot\nabla)B$$

Magnetic separation relies on the principles of magnetism to selectively separate materials based on their magnetic properties. While circular wires are commonly used as field concentrators, systematic studies on how non-circular geometries modify the magnetic field distribution and particle capture efficiency remain limited.

OBJECTIVE



- ➢ The objective of this work is to investigate how the shape of a magnetized collector influences magnetic field gradients and the resulting separation efficiency of magnetic particles in a medium. Specifically, we compare circular and elliptical wire geometries under identical magnetic field and flow conditions.

MATERIAL AND METHOD

Material used			
Paramagnetic	Mn_2O_3	Size = 200 nm	X = 1.77 x10^{-7} m^3/mole

- ➢ To simulate the above system, a finite element-based numerical simulation technique was applied using COMSOL Mutlitphysics 6.1.
- ➢ The coupled problem involves solving three key governing equations; Static magnetic field, Laminar flow, and Transport of dilute species.

COMPUTATIONAL DOMAIN

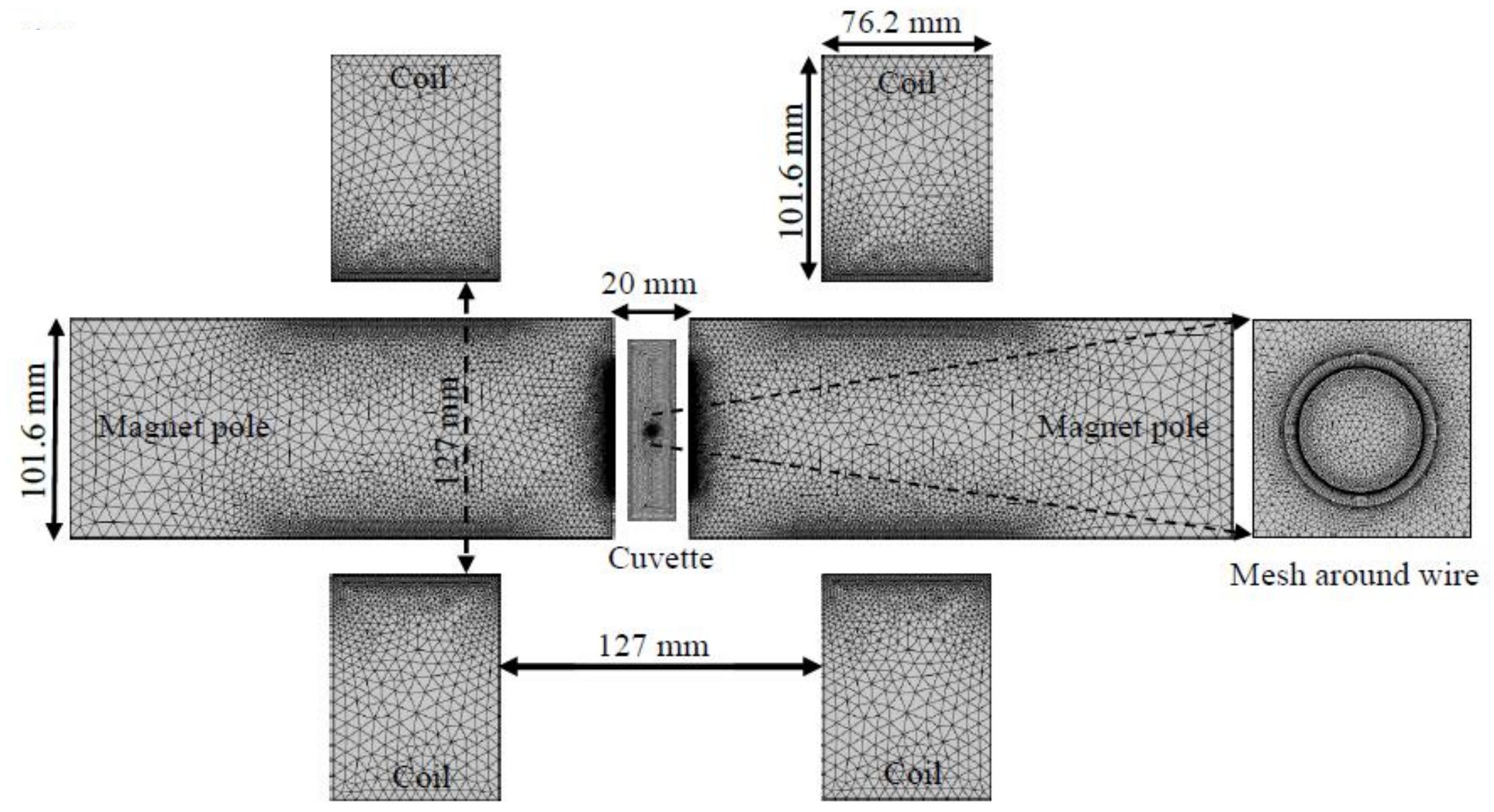


Figure 1: Schematic depicts the computational domain, and its corresponding dimension considered for the present problem. Simulations were conducted in 2D, and the computational domain as discretized into 290804 triangular mesh elements.

GOVERNING EQUATIONS

Mass and momentum balance

$$\nabla \cdot \mathbf{u_f} = 0.$$

$$\rho\left[\frac{\partial \mathbf{u_f}}{\partial t} + \mathbf{u_f}\cdot\nabla\mathbf{u_f}\right] = \mu\nabla^2\mathbf{u_f} + (\rho-\rho_l)\mathrm{g} + \frac{\chi_f}{\eta}(\mathrm{B}\cdot\nabla)\mathrm{B}$$

drag force

$$\mathbf{F}_d = -6\pi\eta R_p \mathbf{v}_{mig}$$

convective-diffusive equation

$$\frac{\partial c}{\partial t} + \nabla\cdot\mathbf{N} = 0$$

$$\text{flux}\quad \mathbf{N}_b = \left[\frac{2R_p^2\Delta\chi}{9\mu_0\eta}c(\mathbf{B}.\nabla)\mathbf{B} + \frac{2R_p^2\nabla\rho}{9\eta}c\mathbf{g}\right].\mathbf{n}$$

RESULTS: MAGNETIC FIELD

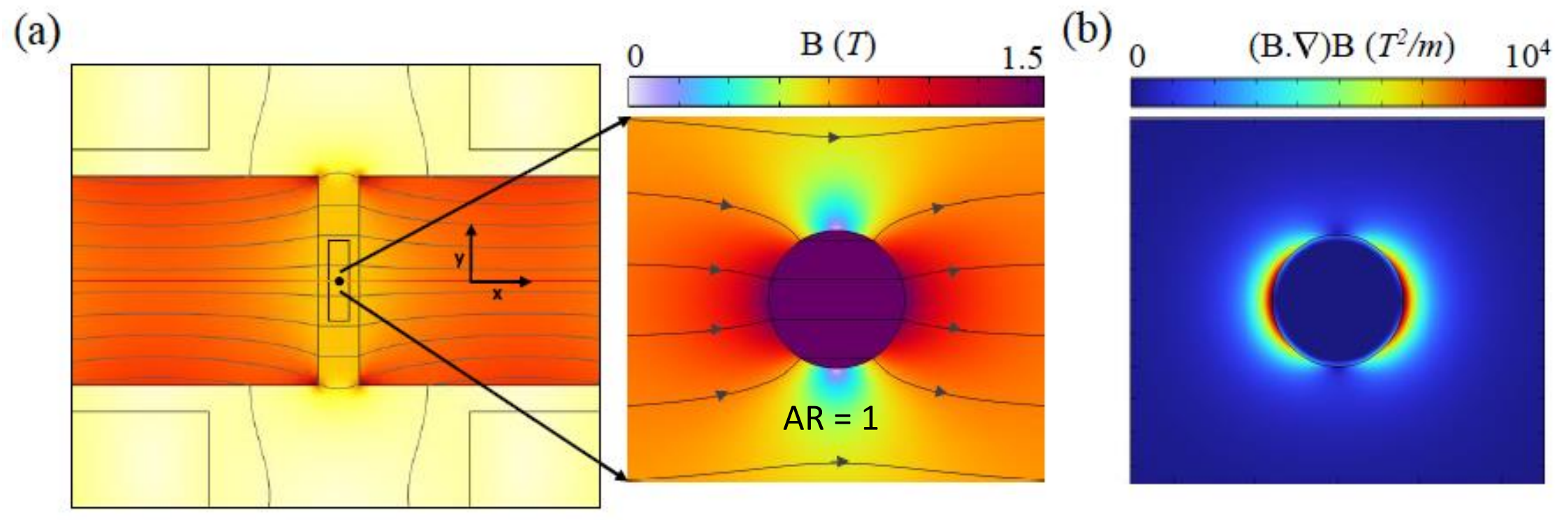


Figure 2: Magnetic flux density profile in a (a) computational domain at 1 T, and the magnetic field lines around a stainless-steel wire, diameter = 0.8 mm. (b) The magnetic field gradient profile (T^2/ m) around a wire at the same conditions.

RESULTS: EFFECT OF ASPECT RATIO

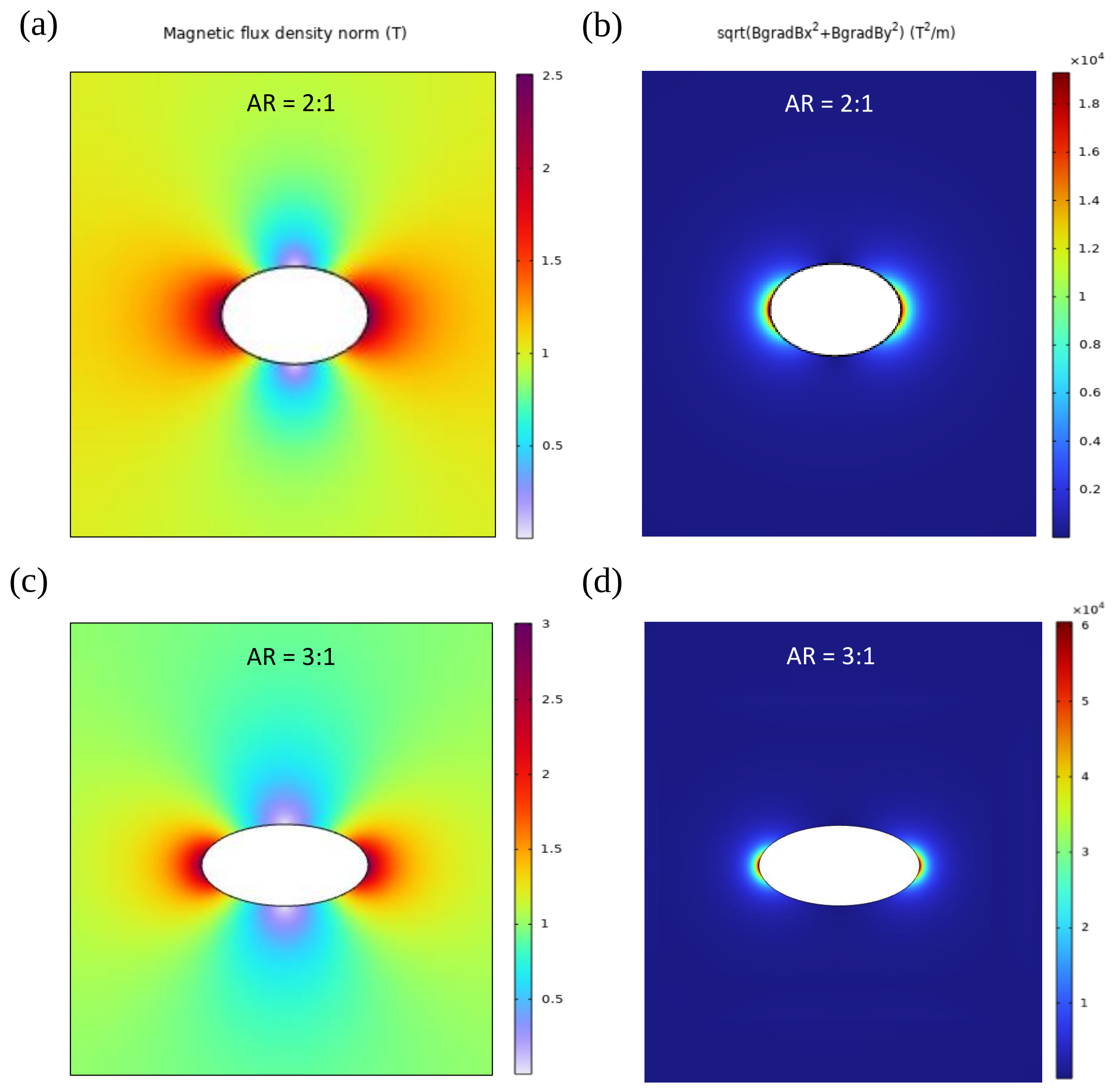


Figure 3. Spatial distribution of magnetic flux density (a) and (c), and magnetic field gradient around a magnetized wire for two different wire aspect ratios. Applied magnetic field is 1.0 T.

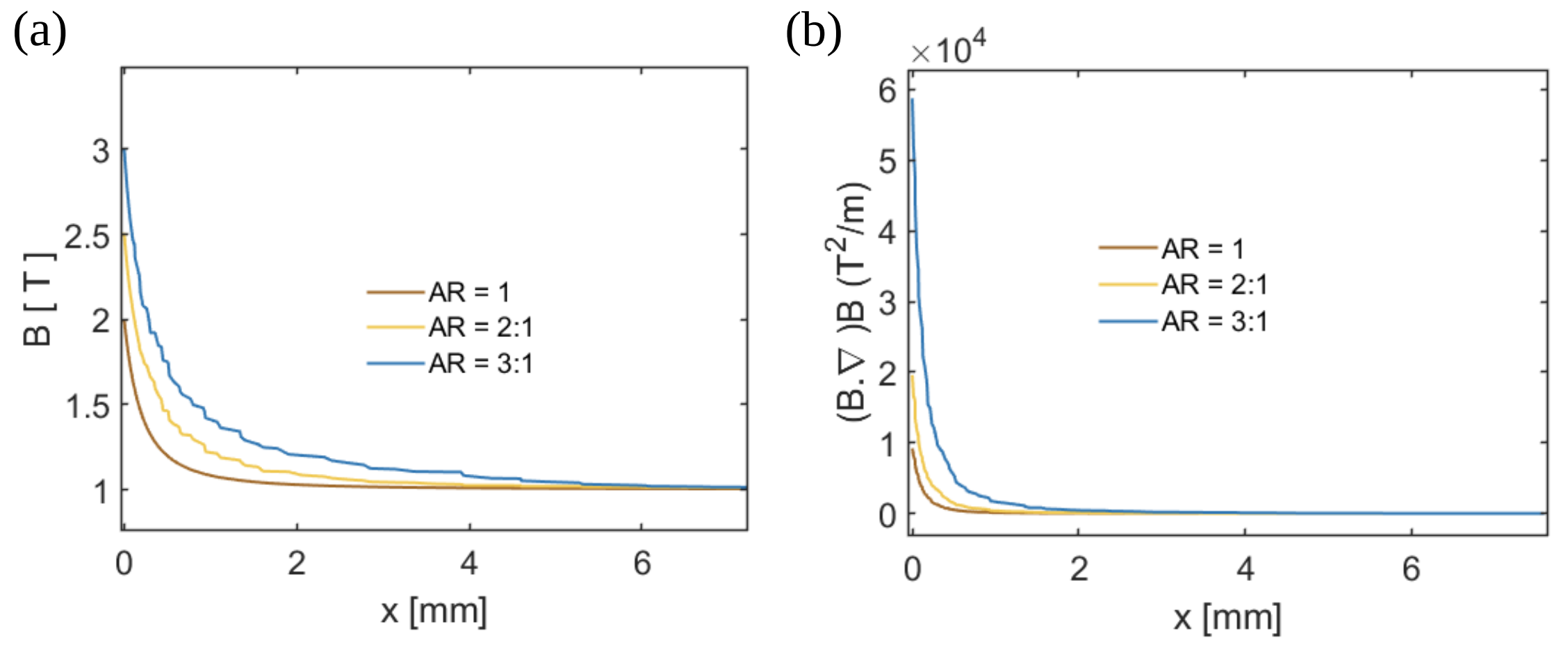


Figure 4. Magnetic flux density (a) and field gradient (b) along the centerline (x) for wires with different cross-sectional aspect ratios (*AR = 1, 2:1, and 3:1*), showing enhanced near-surface field for increasing AR while converging to the background field away from the wire.

PARTICLE SEPARATION

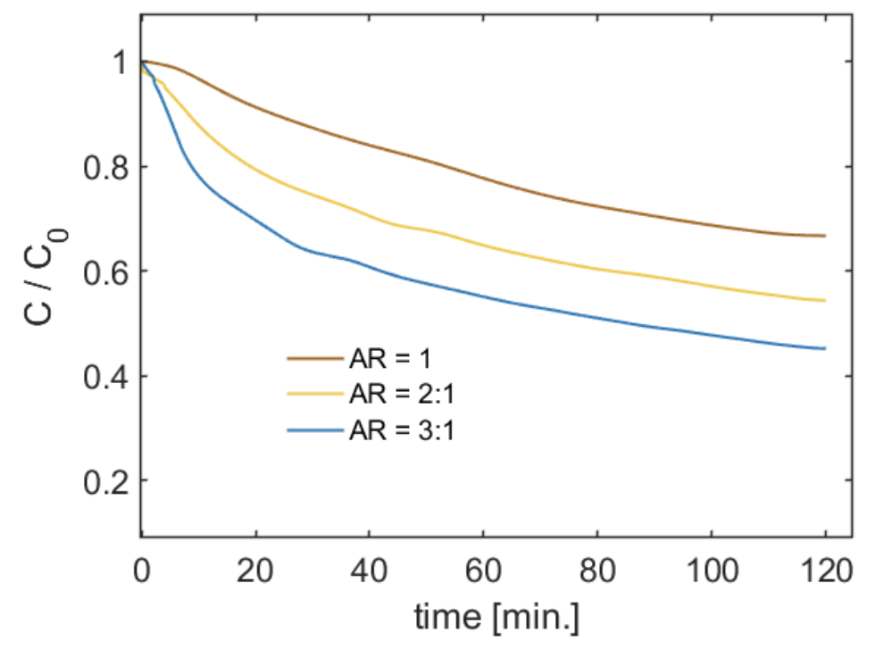


Figure 5: Temporal variation of normalized concentration variation with respect to time for manganese at different aspect ratio (AR) at concentration = 100 mg/L, under magnetic field of B = 1 T.

PARTICLE SEPARATION PROFILE

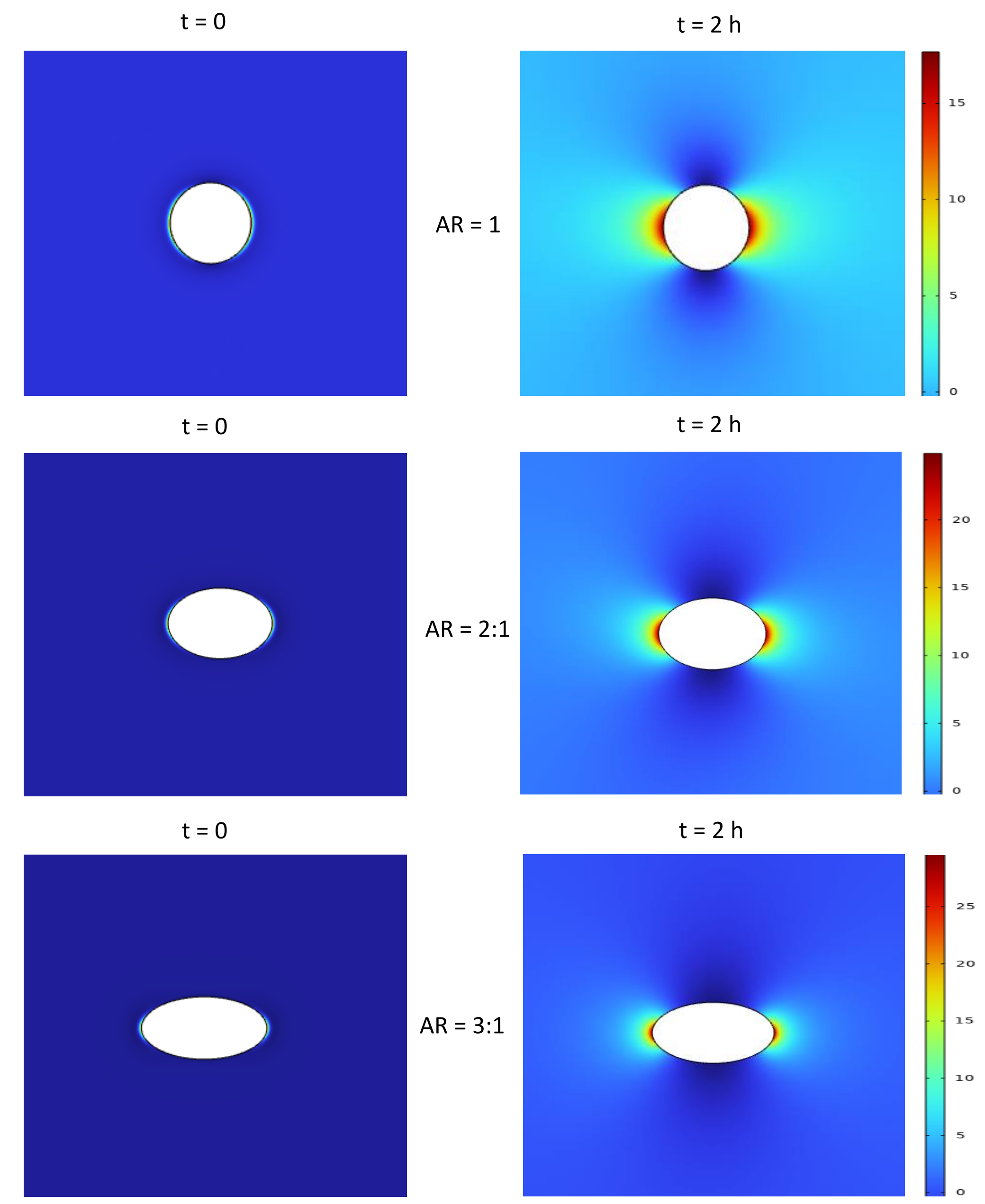


Figure 6: Concentration variation with respect to time for manganese at different aspect ratio (AR) at concentration = 100 mg/L, under magnetic field of B = 1 T.

CONCLUSIONS

I. The results show that paramagnetic particles exhibit strong magnetophoresis, becoming attracted to the peripheries of the wire.

II. Change in wire shape from circular to elliptical leads to the higher magnetic field and its gradient around the wire surface.

III. As the aspect ratio (AR) changes, paramagnetic particle capture improves with time.

IV. These findings demonstrate that wire shape and aspect ratio are powerful design parameters for optimizing high-gradient magnetic separation in vascular-scale systems.

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