Dynamics of Weakly Magnetic Particles under Magnetic Field Gradient

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NATIONAL MAGLAB

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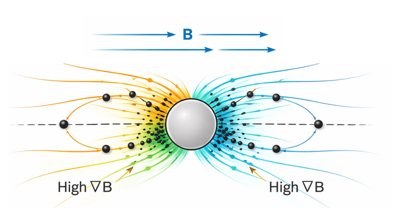
INTRODUCTION

Magnetophoretic transport in non-uniform magnetic fields offers a controlled mechanism for manipulating weakly magnetic microparticles in fluid systems. When a uniform magnetic field magnetizes a ferromagnetic collector (stainless steel 430 wire), strong localized magnetic field gradients are generated normal to the applied field direction.

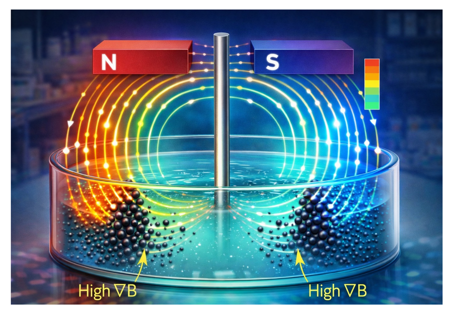


$$\mathbf{F}_m = \frac{V_p \Delta\chi}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B},$$

Under these conditions, particle trajectories deviated from the background flow and resulted in progressive accumulation and deposition along the wire. The localization of particles near the wire surface demonstrates the dominance of gradient-driven magnetic forces over hydrodynamic and diffusive transport.

OBJECTIVE

- To experimentally examine magnetophoretic migration toward a magnetized stainless-steel wire and quantify particle accumulation and cluster formation behavior.
- Compare the response of weakly paramagnetic and nominally diamagnetic particles.



MATERIALS AND METHODS

Material Properties			
Paramagnetic	Mn_2O_3	Size = 5 micron	X = 14100 x10^{-6} cm^3/mole
Diamagnetic	ZnO	Size = 5 micron	X = -27.2x10^{-6} cm^3/mole

- ➢ The particle dynamics were monitored using a ZEISS microscope (Axio zoom.V16) with 13X magnification, allowing real-time visualization of particle migration, clustering, and aggregation behavior during the experiments.
- ➢ To characterize the structural purity of the zinc oxide particles, X-ray diffraction (XRD) analysis was performed.
- ➢ The magnetic response of the zinc oxide particles was further evaluated using a MPMS apparatus. This measurement was used to assess the magnetic behavior of the particles and confirm their weak magnetic nature under the applied magnetic field conditions.

EXPERIMENTAL SETUP

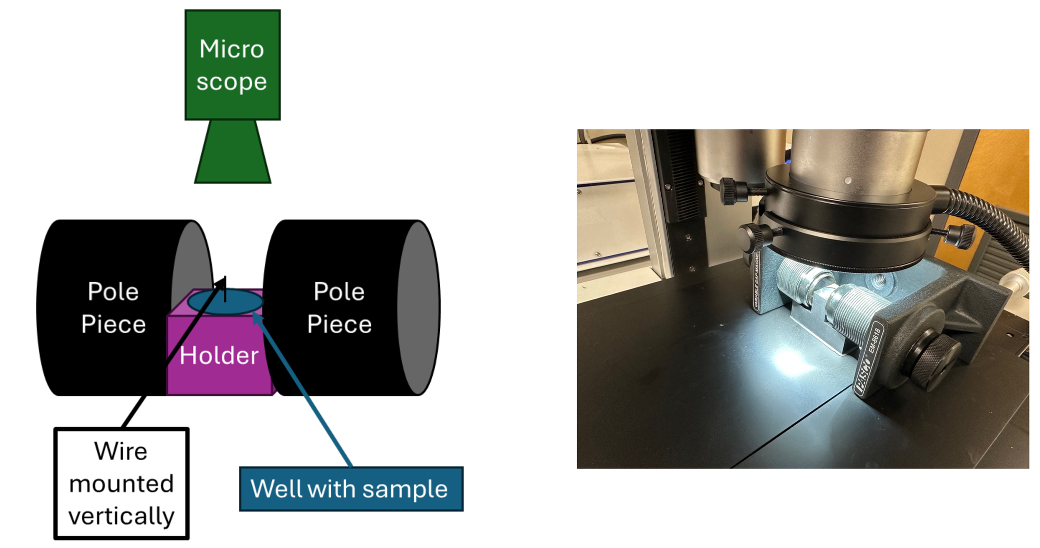


Figure 1: Experimental setup for visualization of magnetically induced particle transport and clustering.

MAGNETIC FIELD

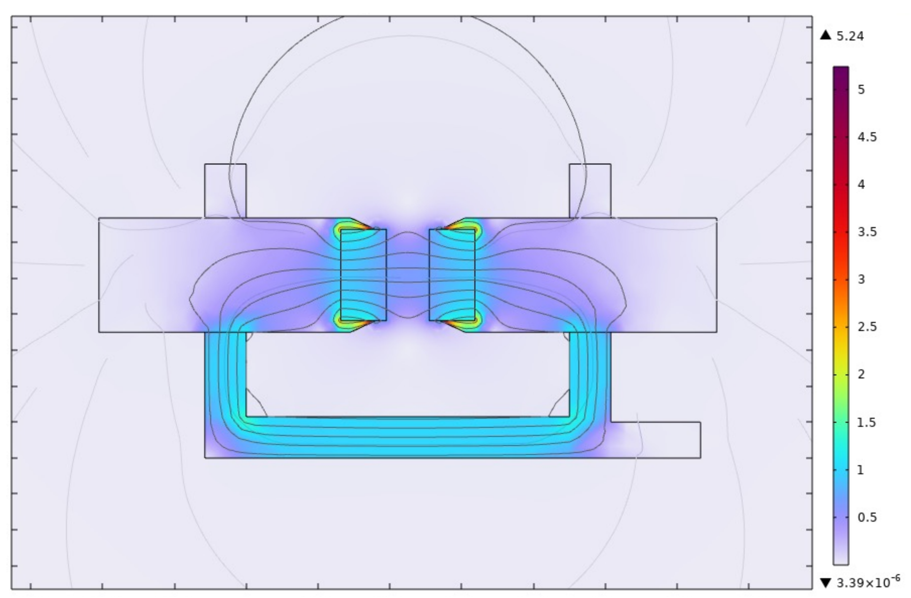


Figure 2: Magnetic flux density distribution profile at an applied magnetic field is 0.7 T.

GOVERNING EQUATIONS

Fluid momentum + continuity

$$\nabla\cdot\mathbf{u} = 0$$

$$\rho\left(\frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \mathbf{f}_m + \rho\mathbf{g}.$$

Magnetic body force:

$$\mathbf{F}_{mp} = \frac{4\pi}{3}\frac{\Delta\chi R_p^3 c}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B};$$

drag force

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

convective-diffusive equation

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

total molar flux

$$\mathbf{N} = -D\nabla c + c(\mathbf{u}_f + \mathbf{v}_{mig})$$

RESULTS: MANGANESE OXIDE

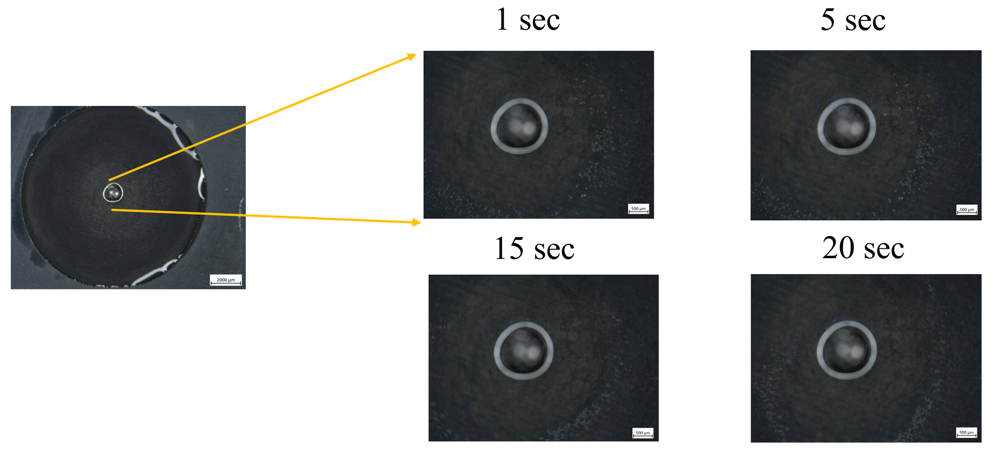


Figure 3: Time-resolved snapshots showing particle aggregation dynamics of manganese oxide at 1 g/L concentration in the absence of an external magnetic field, B = 0 T.

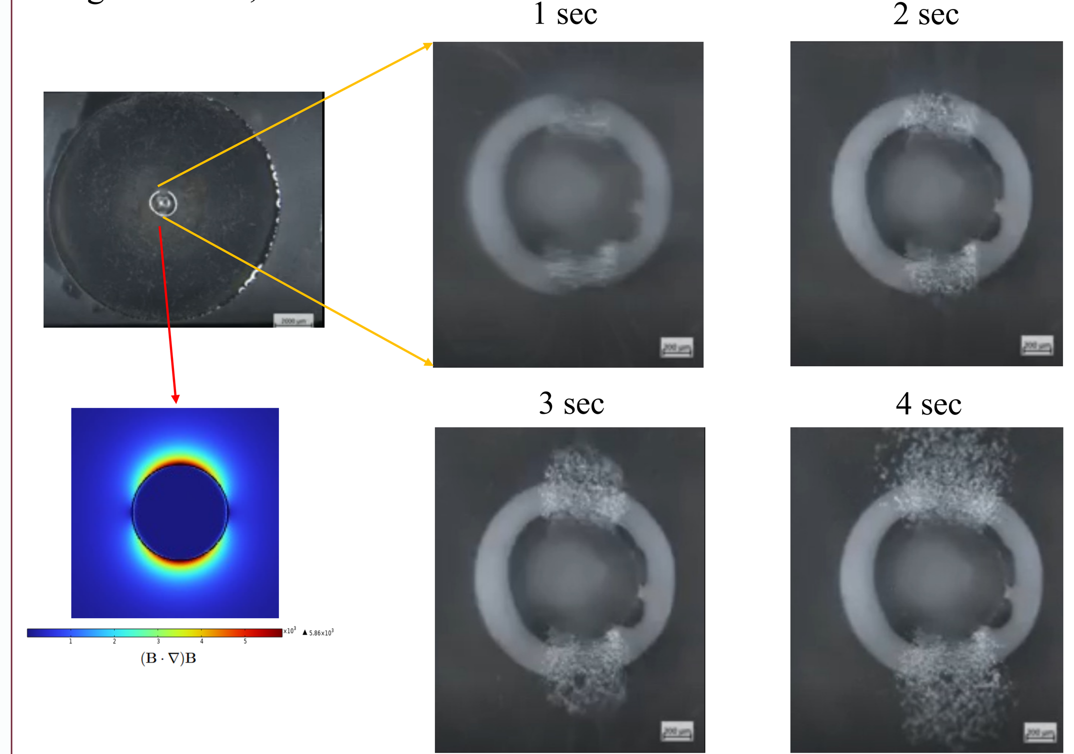


Figure 4: Time-resolved snapshots showing particle aggregation dynamics of **manganese oxide** at 1 g/L concentration around a 1.6 mm wire with an external magnetic field, B = 0.7 T. The contour image below shows the magnetic field gradient profile around a wire.

ZINC OXIDE

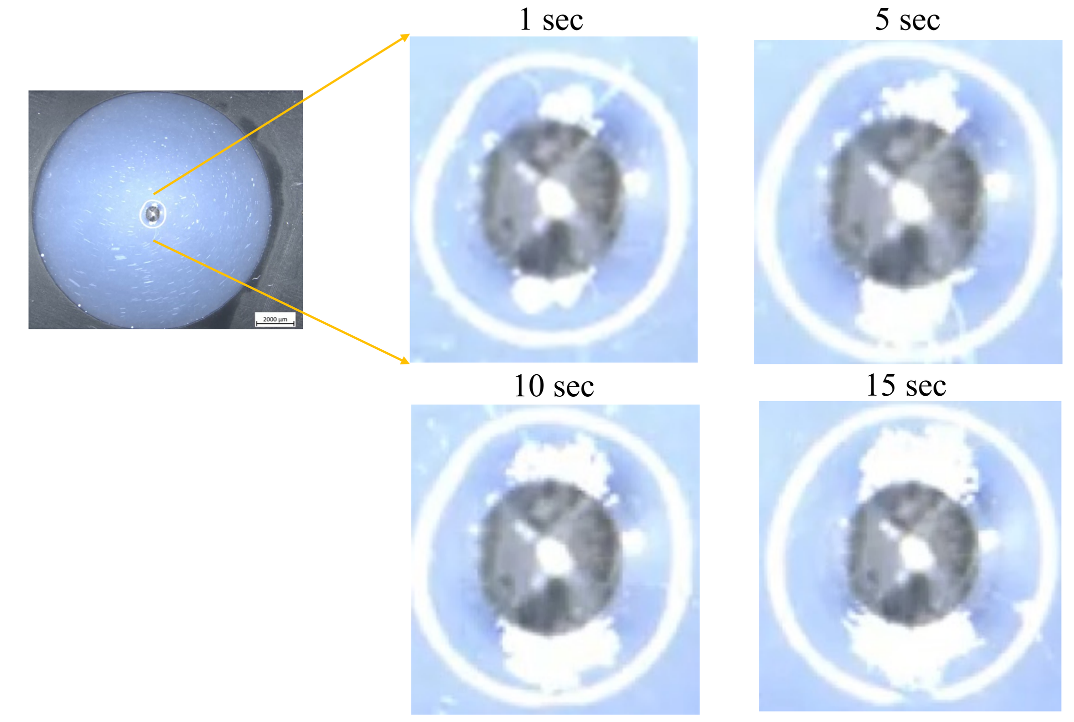


Figure 5: Time-resolved snapshots showing particle aggregation dynamics of **zinc oxide** at 1 g/L concentration around a 1.6 mm wire with an external magnetic field, B = 0.7 T. The contour image below shows the magnetic field gradient profile around a wire.

XRD and MAGNETIC RESPONSE

the peaks highlighted with asterisks are the impurity peaks

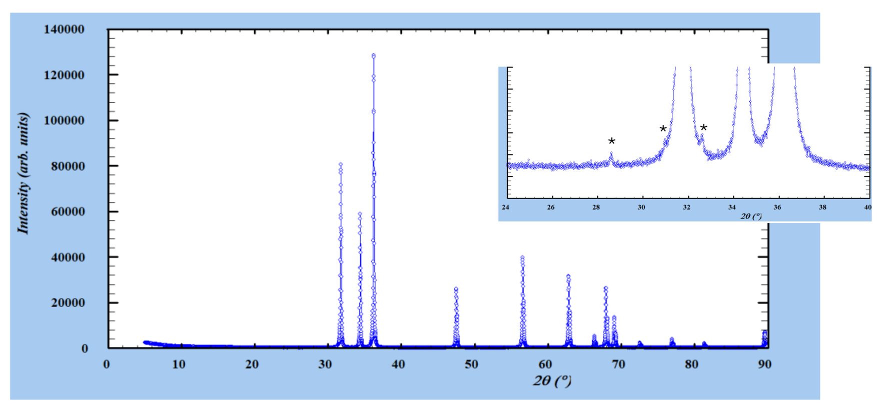


Figure 6: X-ray diffraction (XRD) pattern of the zinc oxide showing the intensity (arb. units) as a function of diffraction angle (2θ). The prominent diffraction peaks confirm the crystalline nature of the material and correspond to the characteristic planes of the primary phase. The inset highlights the 2θ range of 24°–40° for clarity. Peaks marked with asterisks (*) indicate minor impurity phases present in the sample.

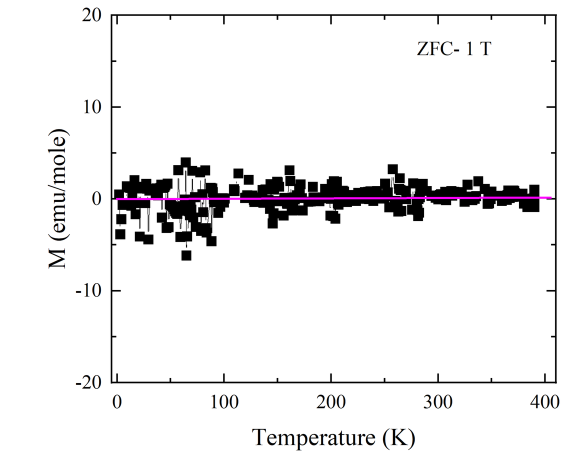


Figure 7: Temperature-dependent magnetization measured under a 1 T magnetic field in the zero-field-cooled (ZFC) mode for zinc oxide. The nearly linear baseline around zero magnetization indicates that the material most likely exhibits extremely weak paramagnetic behavior.

CONCLUSIONS

I. Paramagnetic manganese oxide shows clear migration toward high-gradient regions, followed by clustering and surface deposition near the magnetized wire.
II. Zinc oxide (diamagnetic) responds oppositely under gradient conditions, moving towards the regions of high magnetic field intensity rather than moving away.
III. The presence of a magnetic field gradient is essential; a uniform magnetic field alone does not produce significant separation.
IV. Both manganese oxide and zinc oxide exhibit field-induced clustering under applied magnetic field conditions, indicating that magnetic interactions influence particle–particle assembly in addition to particle transport.
V. Localized field amplification near the wire significantly enhances magnetophoretic forces and particle structuring.

REFERENCES

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