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Clustering and Magnetophoretic Transport of Oxide Microparticles under Uniform Magnetic Fields

NATIONAL MAGLAB

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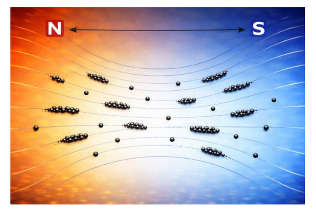
INTRODUCTION

When suspended microparticles are exposed to an external magnetic field, they develop induced magnetic moments that give rise to both translational motion and interparticle interactions. Even in a uniform magnetic field, magnetic dipole–dipole forces can drive particle rearrangement, leading to magneto-migration and the formation of field-induced clusters.

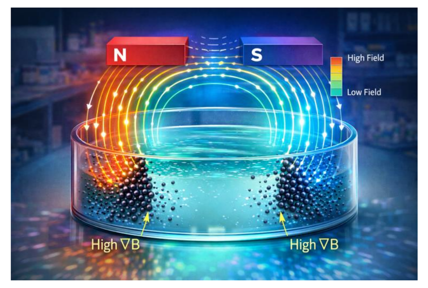


$$F_m = \mu_0 (M.\nabla)H$$

These collective dynamics depend strongly on particle magnetic susceptibility, field strength, and hydrodynamic resistance within the fluid. Understanding how weakly magnetic particles migrate and self-organize under uniform magnetic fields is essential for advancing magnetic manipulation, controlled aggregation, and separation technologies.

OBJECTIVE

- Quantify particle migration behavior under uniform magnetic field.
- Characterize the evolution and morphology of magnetic clusters.
- Compare clustering dynamics between weakly paramagnetic and nominally diamagnetic particles.



MATERIALS AND METHODS

Material Properties			
Paramagnetic	Mn_2O_3	Size = 5 micron	χ = 14100 × 10^{-6} cm^3/mole
Diamagnetic	ZnO	Size = 5 micron	χ = -27.2 × 10^{-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

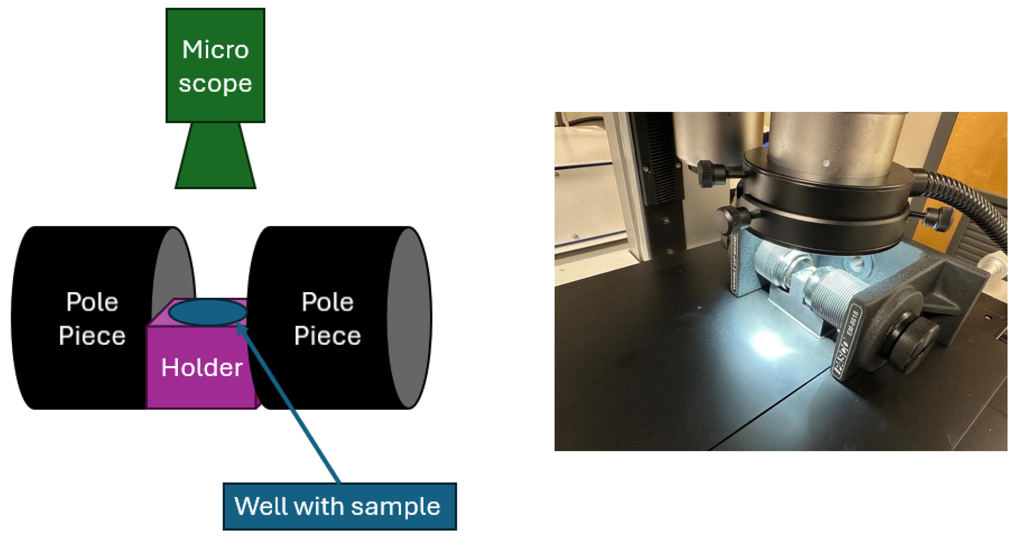


Figure 1: Experimental setup for visualization of magnetically induced particle transport and clustering.

MAGNETIC FIELD

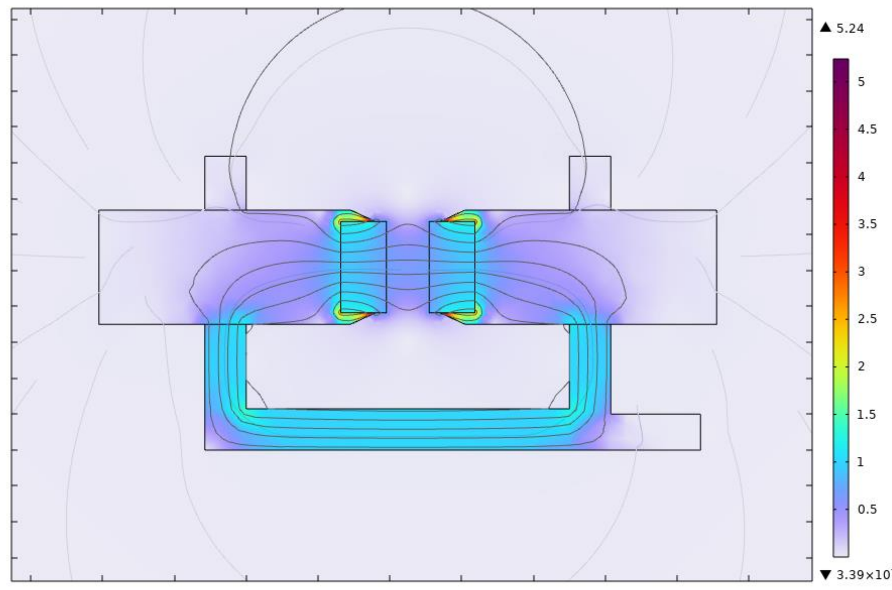


Figure 2: Magnetic flux density distribution profile at an applied magnetic field is 0.7 T.

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:

$$F_m = \mu_0 (M.\nabla)H \qquad B = \mu_0(M+H) = \mu_0(H+\chi H)$$

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

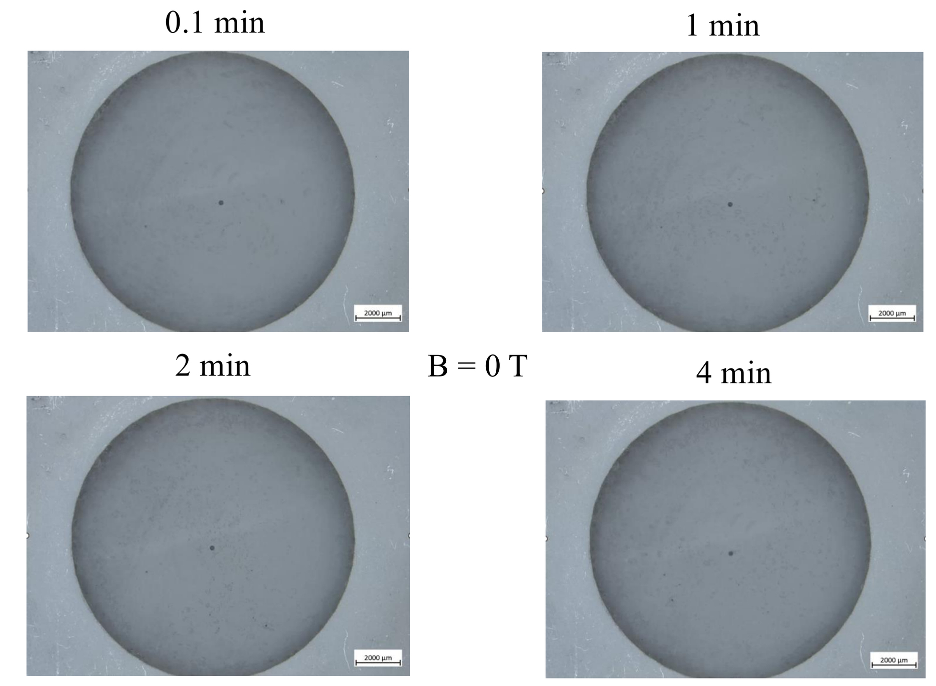


Figure 3: Time-resolved optical snapshots showing particle aggregation dynamics of manganese oxide at 1 g/L concentration in the absence of an external magnetic field, B = 0 T.

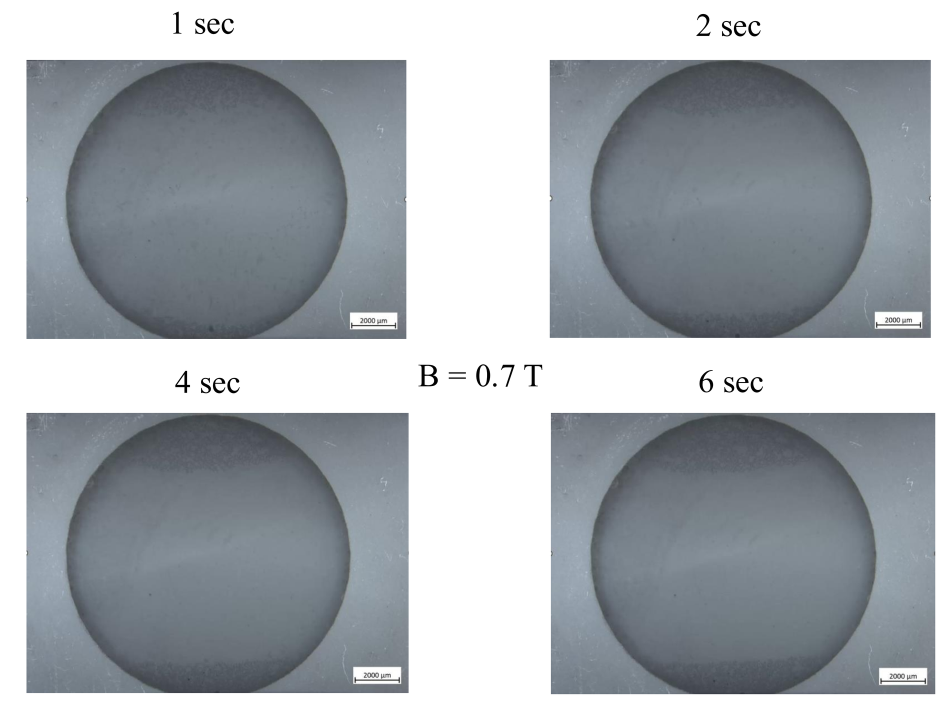


Figure 4: Time-resolved optical snapshots showing particle aggregation dynamics of manganese oxide at 1 g/L concentration and an external magnetic field, B = 0.7 T.

ZINC OXIDE

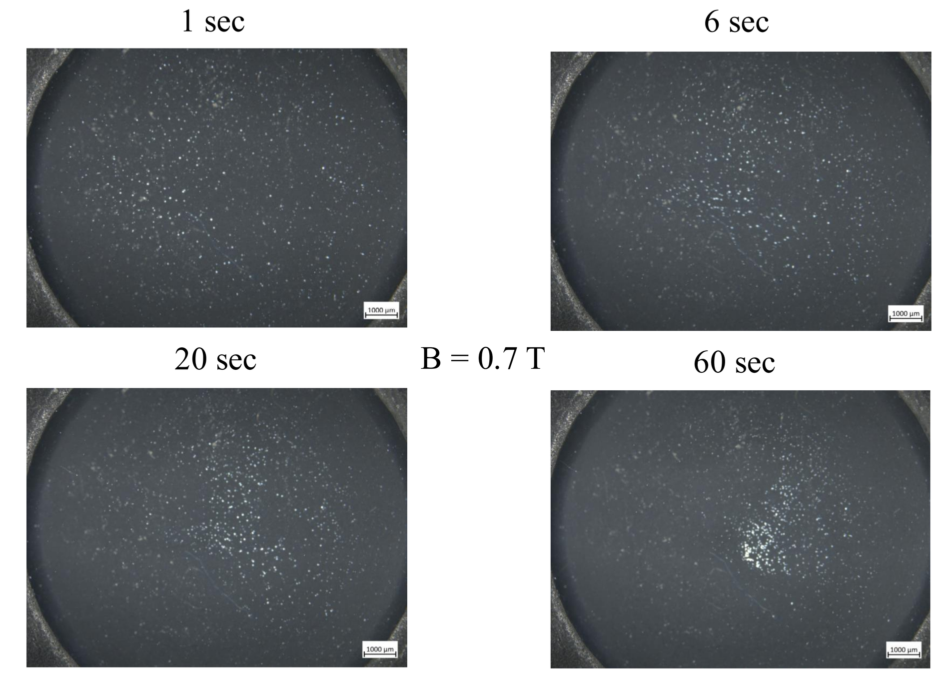


Figure 5: Time-resolved optical snapshots showing particle aggregation dynamics of zinc oxide at 1 g/L concentration and an external magnetic field, B = 0.7 T.

XRD and MAGNETIC RESPONSE

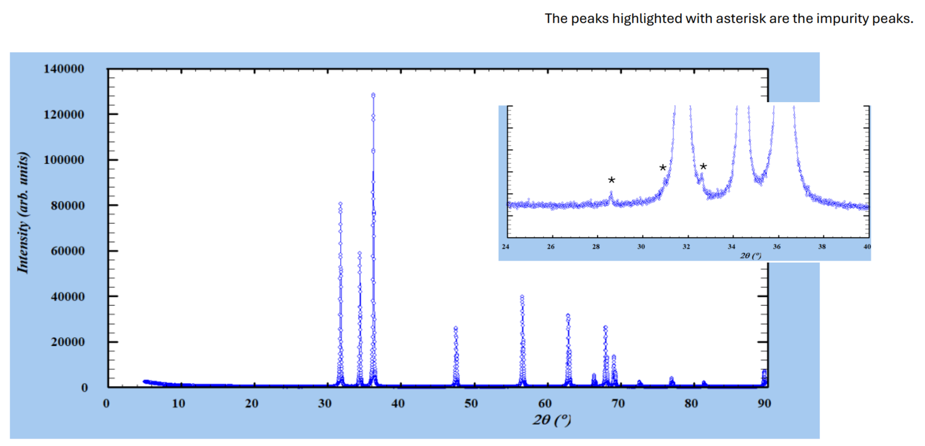


Figure 6: X-ray diffraction (XRD) pattern of the zinc oxide showing the intensity (arb. units) as a function of diffraction angle (2θ). The prominent diffraction peaks confirm the crystalline nature of the material and correspond to the characteristic planes of the primary phase. The inset highlights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

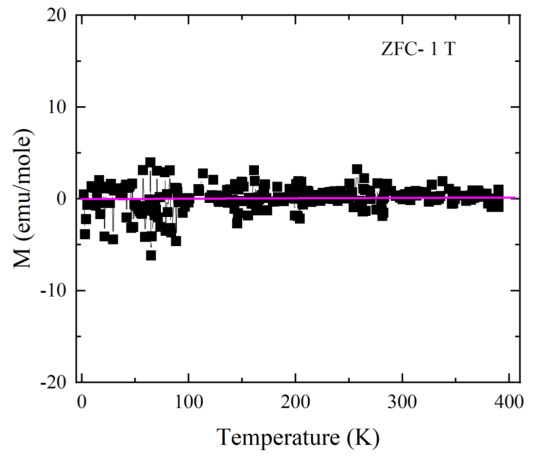


Figure 7: Temperature-dependent magnetization measured under a 1 T magnetic field in the zero-field-cooled (ZFC) mode. The nearly linear baseline around zero magnetization indicates that the material most likely exhibits extremely weak paramagnetic behavior.

CONCLUSIONS

I. Paramagnetic manganese oxide particles show enhanced migration toward regions of stronger magnetic influence and form field-induced clusters over time.
II. The clustering behavior increases with time, indicating that magnetic dipole–dipole interactions promote particle aggregation under applied magnetic fields.
III. Diamagnetic zinc oxide particles exhibit much weaker magnetic response and primarily show slow aggregation driven by non-magnetic interactions, with minimal directional migration.
IV. XRD characterization confirms the crystalline structure and phase impurity of the zinc oxide particles, with diffraction peaks corresponding to the expected ZnO crystal structure.

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ACKNOWLEDGEMENT

I gratefully acknowledge the UROP program for providing the opportunity to mentor an undergraduate researcher and material grant that supported this study. We also thank the National High Magnetic Field Laboratory (MagLab) for access to the facilities and resources that supported this work.