Schlieren-Based Optical Visualization of Metal Ion Dynamics under Uniform Magnetic Fields

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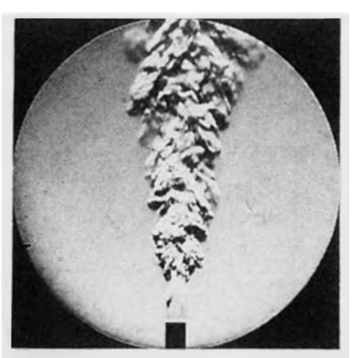
INTRODUCTION

Schlieren imaging provides a powerful, non-invasive optical method to visualize refractive-index gradients arising from spatiotemporal variations in concentration and density.

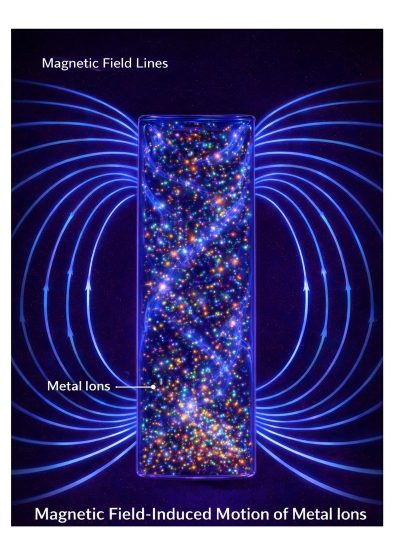
In this work, Schlieren imaging is employed as a non-invasive optical technique to visualize refractive-index gradients arising from spatiotemporal variations in ion concentration and density under the application of a uniform magnetic field.



The observed patterns reflect the competition between magnetic forcing, viscous resistance, molecular diffusion, and gravity-driven convection, providing direct insight into the underlying transport physics.

OBJECTIVE

To experimentally visualize and characterize magnetically induced transport and flow structures of metal ions in liquid media under a uniform magnetic field using Schlieren imaging, and to elucidate the role of magnetic body forces in driving ion redistribution.



MATERIALS AND METHODS

Material Properties			
Paramagnetic	$MnCl_2$	M.W = 125.84 g/mole	X = 14100 x10^{-6} cm^3/mole
Diamagnetic	Li_2SO_4	M.W = 109.94 g/mole	X = - 40 x10^{-6} cm^3/mole

- A Schlieren optical system comprising an LED source, slit, mirrors, pinhole filter, and a scientific camera was used to visualize refractive-index gradients in a liquid-filled glass cuvette placed between magnet poles.
- Time-resolved Schlieren images were acquired during magnetic field application. Post-processing and visualization were performed using custom MATLAB scripts.
- Also, we simulate the magnetic field using finite element-based numerical simulation technique was applied using COMSOL Mutlitphysics 6.1.

EXPERIMENTAL SETUP

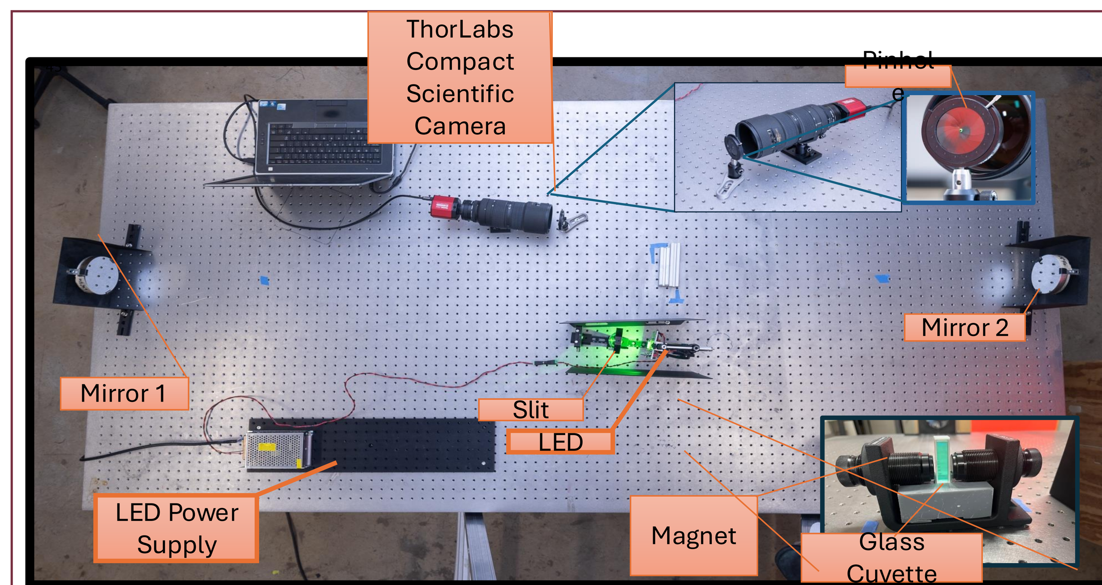


Figure 1: Experimental Schlieren setup for visualization of magnetically induced ion transport.

SCHLIEREN WORKING

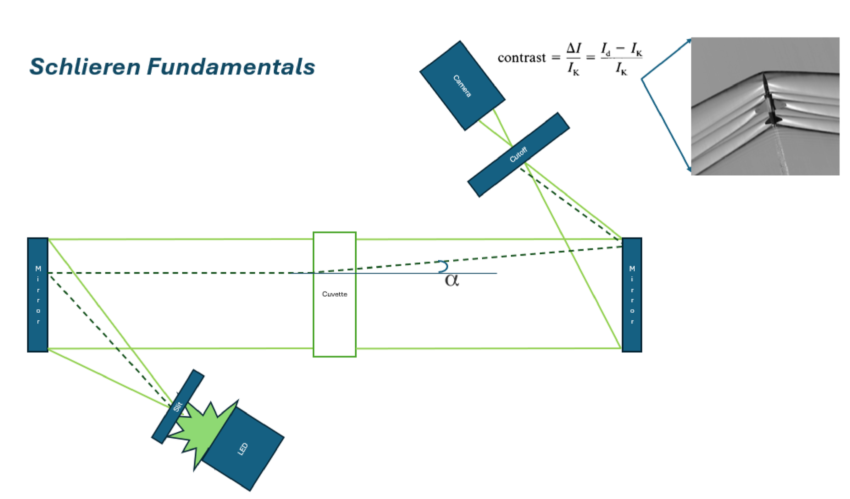


Figure 2: Schematic of the Schlieren imaging principle and optical layout. Light from an LED source is collimated and directed through the test section (cuvette). Refractive-index gradients deflect light rays by an angle α, and a pin-hole (cutoff) placed at the focal plane converts these deflections into intensity variations captured by the camera.

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:

$$\mathbf{f}_m = \frac{1}{2\mu_0}\chi\nabla(B^2)$$

Ion Transport:

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = D\nabla^2 C$$

Intensity–Gradient Relation

$$\frac{\Delta I}{I_k} = \frac{fL}{a_k}\left(\frac{dn}{dC}\right)\frac{\partial C}{\partial y}$$

RESULTS: MAGNETIC FIELD

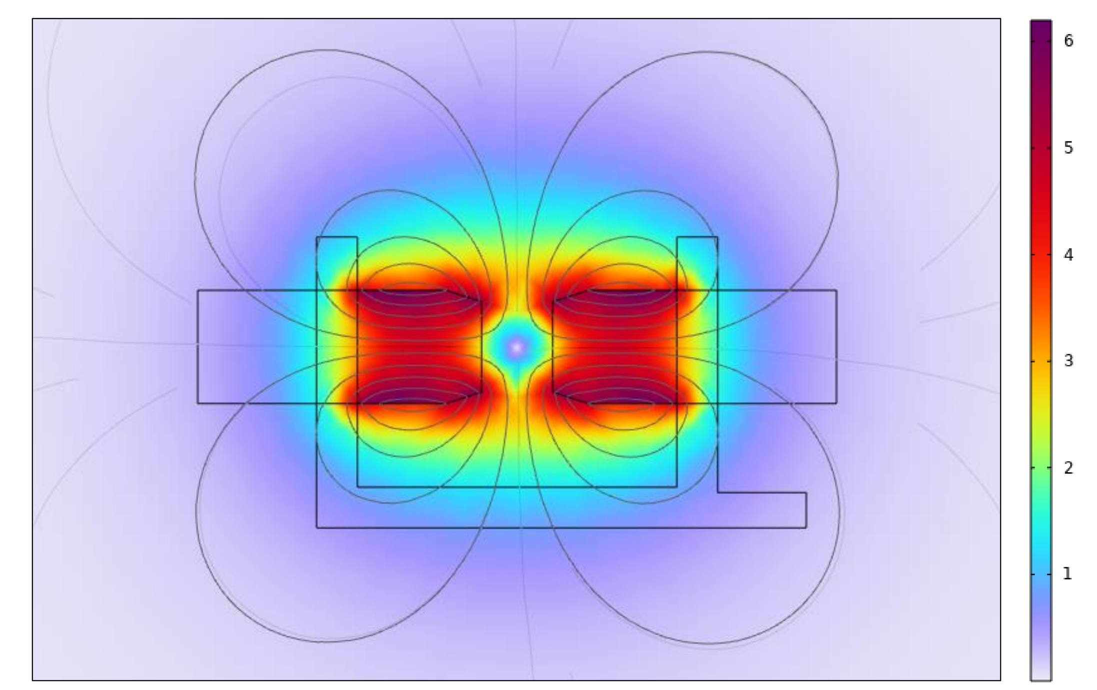


Figure 3: Magnetic flux density distribution profile at an applied magnetic field is 0.7 T.

MANGANESE CHLORIDE

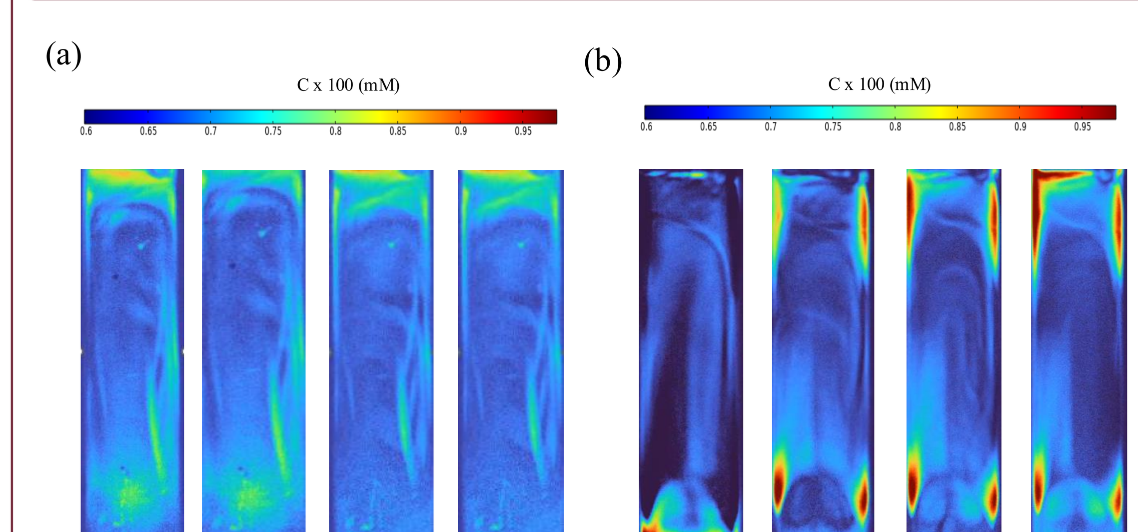


Figure 4: Schlieren-derived concentration maps of manganese solution (100 mM) showing the evolution of concentration distribution under different magnetic field strengths. (a) 0 T (no magnetic field) and (b) 0.7 T.

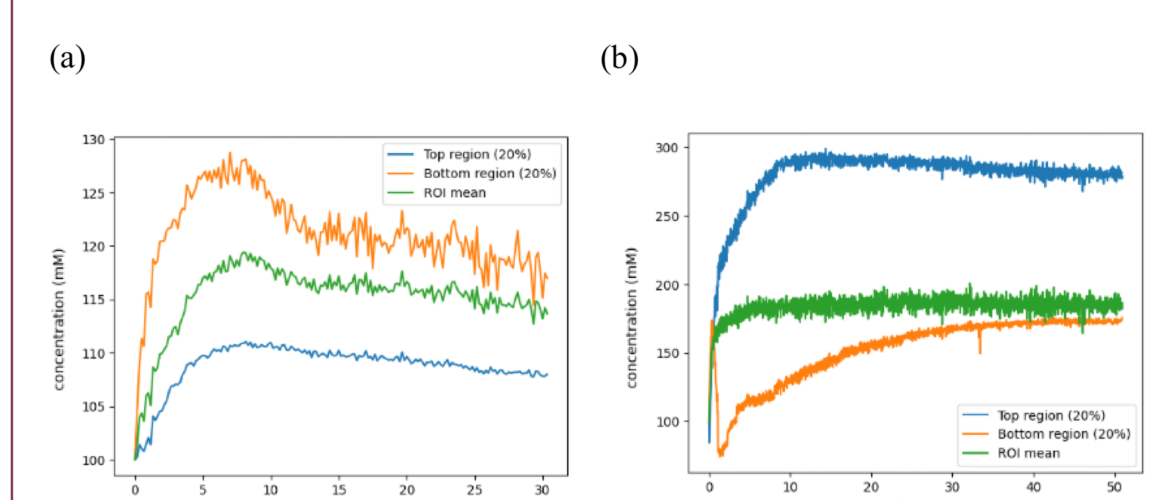


Figure 5: Schlieren-derived concentration evolution of 100 mM manganese under (a) 0 T and (b) 0.7 T with time. The plots show estimated concentration changes in the top region, bottom region, and overall mean within the cuvette. At 0 T, redistribution is governed mainly by natural convection and diffusion, whereas at 0.7 T, enhanced gradients and faster redistribution indicate magnetically induced transport.

LITHIUM SULFATE

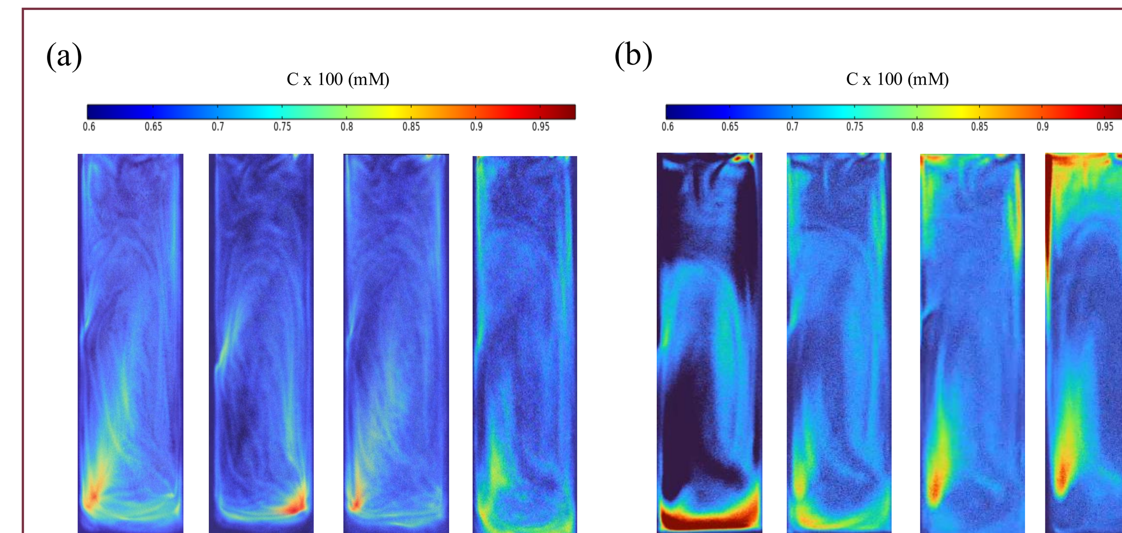


Figure 6: Schlieren-derived concentration maps of Lithium solution (100 mM) showing the evolution of concentration distribution under different magnetic field strengths. (a) 0 T (no magnetic field) and (b) 0.7 T.

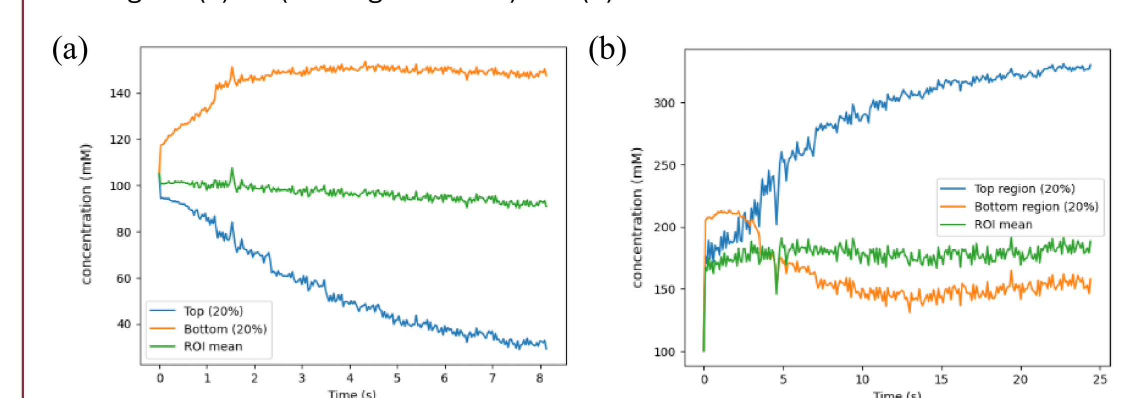


Figure 7: Schlieren-derived concentration evolution of 100 mM Lithium under (a) 0 T and (b) 0.7 T with time. The plots show estimated concentration changes in the top region, bottom region, and overall mean within the cuvette.

CONCLUSIONS

I. An in-house Schlieren imaging system was successfully designed and assembled to investigate the behavior of metal ions under a uniform magnetic field.

II. Direct visualization of dissolved ions is not possible using conventional optical imaging; however, Schlieren imaging enabled indirect observation of ion transport through refractive index gradients.

III. The applied magnetic field significantly influenced ion motion and spatial redistribution within the cuvette.

IV. Paramagnetic ions exhibited migration toward regions influenced by the magnetic field, with pronounced accumulation observed near the top and bottom edges of the magnet.

V. Diamagnetic ions moved away from the magnetic field region due to magnetic repulsion and redistributed toward the upper and lower regions of the cuvette.

VI. The study demonstrates that Schlieren imaging is an effective, non-invasive method for visualizing magnetically induced transport in liquid systems.

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