

**Control of Fluid Flow Using Redox
Magnetohydrodynamics for Chip-Based Microfluidics
and Analytical Applications**

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The use of magnetohydrodynamics (MHD) to control liquid flow in small volumes for portable devices will be presented. Discussion will focus on microfluidic pumping and chemical analysis measurements.

In MHD, fluid flow results from a Lorentz force that has a magnitude and direction equal to the cross product of current and magnetic induction vectors. Thus, we can design portable devices with appropriate geometries that take advantage of this right-hand rule to generate a fluid flow with desired direction and magnitude. Control of flow in this way can be performed without moving parts, in aqueous and non-aqueous solutions, within a large variety of device materials, while allowing reversal of flow without valves.

MHD is a fairly new pumping method to small scale, non-mechanical solution fluidics. Jang *et al.*¹ have described a microfluidic system that uses a constant voltage (e.g. 10 to 60 V) to generate dc current in aqueous electrolyte in the presence of constant magnetic fields from permanent magnets. A major problem is that electrolysis of water occurs and bubbles are generated. Lemoff and Lee² have described a system that uses an ac current in aqueous electrolyte with an ac magnetic field from a small electromagnet. The ac method is dominated by charging current, instead of faradaic current. The ac method is also more complicated, requiring variable-field magnets (electromagnets) and a synchronous phase with the ac current. H. Bau and co-workers³ demonstrated MHD with permanent magnets on electrolytes for pumping and stirring applications, with either dc or alternating voltages at multiple electrodes. Bubble formation and electrode lifetime are issues. Recently, Manz and co-workers have constructed a circular ac MHD pump for chromatographic applications.⁴ Leventis and co-workers⁵ have taken advantage of redox species in a macroscopic fluidic device, which produces flow when a current is generated galvanically.

In our approach, low potentials (10 mV – 100's mV) are applied to generate a current in solutions of redox species, which undergo oxidation and reduction, in the presence of magnetic fields. Thus, current is controllable, bubble generation is avoided, the system remains dc-based, and ultimately, the use of permanent magnets for miniaturization is possible. Fundamental studies of magnetic field effects on redox-containing electrochemical systems performed by White⁶ and Leventis⁷ serve as a foundation for our fluidics approach.

We will present our latest developments in redox-based MHD microfluidics on a chip. Low temperature co-fired ceramic materials were used to construct prototype microfluidic devices. These materials allow easy assembly of three-dimensional structures that integrate channels and electrodes. Contact to electrodes was made with edge connectors. A potentiostat was used

to apply voltages and measure current in the presence and absence of magnetic fields. Magnetic field strengths from 0 to 1.77 T were investigated with an electromagnet, but rare-earth permanent magnets (~0.55 T) demonstrate portability. Effects on flow rate of different redox species, concentrations, solvents, and electrolyte will be discussed, which help to define the best geometries, dimensions, and conditions for optimized redox MHD microfluidics and the suitable applications for it.

We will also present studies where MHD can be used to significantly enhance signals in analytical chemistry measurements. One example is in trace metal analysis. By inducing convection with MHD during the preconcentration step of anodic stripping voltammetry (ASV) analysis, the resulting signal (using a linear sweep) increases. The higher flux of metals due to MHD allows a higher quantity deposited at the electrode during the preconcentration step. We have reported signal increases of 160% (in a 1.77 T field, compared to 0 T) for concentration of 10^{-6} to 10^{-7} M of copper, cadmium, and lead from solutions of 40 mM $\text{Hg}(\text{NO}_3)_2$, 30 mM HNO_3 , and 0.1 M KNO_3 .⁸ Current from reduction of high concentrations of Hg^{2+} generates the MHD. However, when the high concentration of Hg^{2+} is replaced with 100 mM Fe^{3+} , (while maintaining 1 mM $\text{Hg}(\text{NO}_3)_2$ to achieve a thin mercury film electrode), the signal is about 3 times at 1.77 T, compared to 0 T, and does not suffer from heavy metal contamination that occurs when high concentrations of mercury are used. Detection limits of 10^{-9} M or better are expected, which is of interest in portable trace metal devices and in measurements of small volumes, in which stirring is often complex or prohibitive. Considerations of the limitations to volume and electrode size will also be discussed.

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