ABSTRACT

Efficient mixing in microfluidic systems remains a formidable challenge due to the inherently laminar flow characteristics at the microscale, where Reynolds numbers are typically below one. The absence of turbulence in microchannels confines mixing primarily due to molecular diffusion—an inherently slow process that limits the performance of microfluidic devices in various applications including chemical synthesis, biological assays, and medical diagnostics. This thesis presents a comprehensive investigation into the design, analysis, and performance optimization of electroosmotic micromixers with novel geometric configurations to enhance mixing efficiency at the microscale.

The research explores four innovative microchamber geometries: circular, diamond, diamond split-and-recombined (DSAR), and square split-and-recombined (SSAR) designs. For each configuration, a systematic numerical analysis examines the effects of critical design parameters and operational conditions on mixing performance. The key parameters investigated include chamber dimensions, inlet velocity, AC voltage amplitude, frequency, electrode length, and phase difference between electrode potentials. The numerical approach employs finite element modeling with appropriate mesh refinement and validation against experimental data from the literature to ensure the accuracy and reliability of the results.

The circular chamber micromixer investigation reveals that smaller chamber diameters (20 μm) produce superior mixing through enhanced electroosmotic vortex interactions, achieving an efficiency of approximately 98% under optimal conditions (energy requirement: 500mV). Diamond chambers, designed with flat walls to facilitate electrode fabrication, demonstrate improved mixing performance through effective stretching and folding of fluid interfaces, reaching efficiencies of up to 99% with optimal parameters (energy requirement: 500mV).

A significant advancement is introduced through the novel diamond split-and-recombined (DSAR) configuration, which incorporates internal obstacles to synergistically combine passive and active mixing mechanisms. This design creates complex flow patterns through forced separation and recombination of fluid streams, achieving mixing efficiencies exceeding 99% with optimal obstacle dimensions (15 μm) and electrode configurations (energy requirement: 300mV). Further innovation is demonstrated with the square split-and-recombined (SSAR) design featuring nonaligned inlet-outlet channels, which substantially enhances mixing through induced recirculation patterns while simplifying fabrication. By optimizing electrode polarity arrangements and operational parameters, the SSAR configuration achieves mixing efficiencies of up to 99.36% at significantly reduced operational voltages (energy requirement: 250mV).

Comparative analysis shows that split-and-recombined micromixers (DSAR and SSAR) outperform conventional circular and diamond designs, with the SSAR achieving the best balance between mixing performance and fabrication simplicity. The voltage required for peak efficiency decreased from 500 mV in baseline designs to 300 mV in the DSAR and 250 mV in the SSAR, reflecting 40% and an additional 16.7% reduction in energy demand, respectively. Optimal inlet velocity remained within 100–150 μm/s for all designs, while the SSAR exhibited the widest frequency stability range and greatest operational flexibility, confirming the superior electrokinetic efficiency of split-and-recombine geometries.

This research contributes significantly to the field of microfluidics by demonstrating how strategic integration of electroosmotic actuation with optimized chamber geometries can dramatically enhance mixing performance at the microscale. The insights gained from this work have important implications for the development of more efficient lab-on-a-chip devices, particularly for applications requiring rapid and homogeneous mixing of reagents, biological samples, or nanoparticles under controlled microfluidic conditions.