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Optimizing AC Electroosmotic Flow Patterns Through Insulator-Based Microchannel Design

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Abstract

Efficient fluid control is one of the most important requirements in microfluidic systems used for biomedical analysis, chemical processing, and lab-on-a-chip devices. AC electroosmotic (AC-EOF) flow is a useful technique because it generates liquid movement without mechanical pumps or moving components. Most previous studies have focused on modifying electrode geometry to control fluid flow. In contrast, this study investigates how the shape of insulating structures placed between two parallel electrodes can influence AC electroosmotic flow.

Different microchannel cross-sections, including parallelogram and modified rectangular geometries, were examined to understand their effect on vortex formation. Experimental observations using fluorescent microparticles showed that different channel shapes produced different flow behaviors. A parallelogram-shaped channel generated a single circulating vortex, whereas channels with non-orthogonal corners produced two distinct vortices. Numerical simulations supported these experimental findings and demonstrated that the geometry of the insulating material changes the distribution of electric field lines, which directly affects fluid motion.

The results indicate that careful design of insulating structures can effectively control electroosmotic flow without changing electrode configurations. This approach provides a simple and flexible method for improving fluid mixing, enhancing mass transport, and increasing the performance of microfluidic devices. The proposed design strategy may also support future developments in particle manipulation, chemical analysis, and biomedical applications.

Keywords: AC electroosmosis, Microfluidics, Electroosmotic flow, Insulator geometry, Vortex flow, Electric field, Lab-on-a-chip.

Introduction

Microfluidic technology has become an important research area because it allows precise handling of very small volumes of liquids. These systems are widely used in medical diagnosis, chemical analysis, biological research, environmental monitoring, and pharmaceutical industries. One of the major challenges in microfluidic devices is achieving efficient mixing of fluids because liquid flow inside microchannels is generally smooth and laminar. Under such conditions, mixing occurs mainly through diffusion, which is usually slow and inefficient.

To improve mixing, researchers have developed several active and passive techniques. Passive methods depend on the shape of the channel to disturb the flow, while active methods use external forces such as electric, magnetic, acoustic, or thermal energy. Among these techniques, AC electroosmotic flow has gained considerable attention because it can generate controlled fluid motion without using mechanical pumps or moving parts.

In a conventional AC electroosmotic system, two closely spaced electrodes are placed on the same surface of a microchannel. When an alternating electric field is applied, ions near the electrode surfaces move periodically. The interaction between the electric field and the charged ions creates a steady fluid motion known as AC electroosmotic flow. The efficiency of this process depends on several factors, including applied voltage, operating frequency, electrolyte properties, and electrode geometry.

Most earlier investigations have concentrated on modifying electrode arrangements to obtain different flow patterns. Although this approach has produced useful results, changing electrode designs often increases fabrication complexity and manufacturing cost. Therefore, alternative methods that can control flow without redesigning the electrodes are highly desirable.

The present study introduces a different strategy by focusing on the shape of insulating materials positioned between two parallel electrodes. Instead of changing the electrodes themselves, the geometry of the insulating channel is modified to influence the local electric field. Since electric field distribution directly controls electroosmotic flow, changing the channel geometry provides an effective way to generate different vortex patterns.

Two different channel designs were investigated in this work. The first design used a parallelogram-shaped cross-section, while the second employed a rectangular channel with non-right-angle corners. Experimental observations and numerical simulations were performed to compare the resulting flow structures. The study demonstrates that even small geometric modifications in the insulating material can significantly influence fluid circulation inside the microchannel.

The findings provide a practical approach for improving mixing efficiency and fluid transport in microfluidic systems. Because this method does not require complicated electrode fabrication or additional moving components, it has potential applications in lab-on-a-chip devices, biochemical sensors, microreactors, and particle manipulation technologies.

Background and Working Principle of AC Electroosmotic Flow

AC electroosmosis is an electrokinetic phenomenon in which an alternating electric field generates controlled fluid motion near the surface of electrodes. Unlike pressure-driven flow, AC electroosmosis relies entirely on electrical forces, making it highly suitable for miniature fluidic systems where conventional pumping methods become difficult to implement.

When an AC voltage is applied between two electrodes immersed in an electrolyte, ions accumulate near the electrode surfaces and form an electrical double layer. As the electric field changes direction during each AC cycle, the ionic charges also change accordingly.

However, the interaction between the electric field and the induced charges continuously produces a tangential electrical force that drives the surrounding liquid along the electrode surface.

The movement of the liquid depends on several operating conditions. Parameters such as voltage amplitude, signal frequency, electrolyte conductivity, channel dimensions, and electrode spacing all influence the resulting flow pattern. Proper adjustment of these factors can generate circulating vortices that significantly improve mixing inside microchannels.

Traditional AC electroosmotic systems achieve flow control mainly by designing electrodes with different shapes or arrangements. In the present work, however, the electrodes remain unchanged while the insulating material between them is redesigned. This alternative approach simplifies device fabrication while still providing effective control over the fluid motion.

Theory and Numerical Simulation

To understand how the proposed microchannel design controls fluid motion, both theoretical analysis and numerical simulation were carried out. The objective was to explain how the geometry of the insulating material changes the electric field distribution and, consequently, the AC electroosmotic flow inside the channel. The study focused on the relationship between channel shape, electric field direction, and vortex formation.

In an AC electroosmotic system, the electric field generated between two electrodes interacts with ions present in the electrolyte. These ions accumulate near the electrode surface and form an electrical double layer. When an alternating voltage is applied, both the electric field and the ionic charges change direction continuously. Even though the polarity changes every half cycle, the combined interaction produces a steady driving force that moves the liquid along the electrode surface.

The proposed design introduces insulating structures between the electrodes. These structures modify the local electric field by changing the direction of the field lines. As a result, different flow patterns develop depending on the geometry of the channel walls. This concept forms the basis of the present flow-control strategy.

The theoretical investigation indicates that the angle formed between the channel wall and the electrode plays a significant role in determining the direction of the fluid flow. Acute corners and obtuse corners influence the surrounding electric field differently. Consequently, they generate different electroosmotic flow directions near the channel boundaries.

Numerical simulations were performed to predict the electrical potential distribution and the resulting flow field. The Laplace equation was solved to determine the electric potential inside the microchannel. Based on the calculated electric field, the electroosmotic slip velocity along the electrode surfaces was estimated. These calculations provided a detailed picture of the expected flow behavior before conducting experiments.

The simulation results revealed that channel geometry strongly influences vortex formation. In the parallelogram-shaped channel, the flow vectors combined to form one continuous circulation loop, producing a single vortex. In contrast, channels containing non-orthogonal corners generated opposing flow directions that resulted in two separate vortices. These predictions were later confirmed through experimental observations.

Overall, the theoretical and numerical analyses demonstrate that modifying only the insulating channel geometry provides an efficient method for controlling electroosmotic flow without changing the electrode configuration. This approach simplifies device design while maintaining effective flow control.

Materials and Methods

Experimental investigations were carried out using specially fabricated transparent microfluidic devices equipped with conductive electrodes. The purpose of the experiments was to compare the fluid flow generated in different channel geometries under identical electrical operating conditions.

Two different channel designs were prepared for the study. One device contained a parallelogram-shaped cross-section, while the second employed a rectangular channel with non-right-angle corners. These geometries were selected because theoretical analysis suggested that corner shape would significantly influence vortex formation.

The microfluidic chips were fabricated using transparent fused silica substrates coated with indium tin oxide (ITO). The ITO layers served as transparent electrodes positioned on the upper and lower surfaces of the channel. This arrangement allowed electrical excitation while simultaneously enabling microscopic observation of particle motion.

Negative epoxy photoresists were used to fabricate the insulating channel structures. Different fabrication techniques ensured that the desired channel geometries were accurately reproduced while maintaining uniform channel dimensions.

To visualize liquid motion, fluorescent microparticles suspended in a dilute potassium nitrate solution were introduced into the microchannels. Different particle sizes were selected depending on the type of measurement being performed. Smaller particles were used for two-dimensional flow visualization, whereas larger fluorescent particles were employed for three-dimensional trajectory analysis.

All aqueous solutions were prepared using highly purified deionized water to minimize contamination and maintain stable electrical properties throughout the experiments.

Fabrication of the Microfluidic Device

The fabrication process was designed to produce transparent and electrically conductive microfluidic chips suitable for both electrical excitation and microscopic observation. Initially, thin conductive indium tin oxide coatings were deposited onto polished fused silica wafers using a sputtering technique. After deposition, the coated substrates were heated at high temperature to improve electrical conductivity and increase the stability of the conductive layer.

Following electrode preparation, the microchannel structures were fabricated using photolithographic techniques. Negative epoxy photoresists were patterned to obtain the required channel geometries. Care was taken to ensure that the parallelogram and modified rectangular channels possessed smooth and accurately defined walls.

Access holes were then prepared to allow the introduction of liquid samples into the channels. Finally, the upper and lower substrates were assembled to create enclosed microfluidic devices containing transparent electrodes on opposite sides of the channel. The transparent design allowed continuous observation of particle motion throughout the experiments while maintaining uniform electrical excitation across the microchannel.

Experimental Procedure

After fabrication, the microfluidic devices were connected to an AC voltage source. An alternating electrical signal was applied between the upper and lower electrodes while fluorescent particles suspended in the electrolyte moved inside the channel. Their trajectories were recorded using a high-resolution fluorescence microscope equipped with an image acquisition system.

For three-dimensional flow analysis, General Defocusing Particle Tracking (GDPT) was employed. Before the actual experiment, the optical system was calibrated by recording images of stationary particles positioned at different heights. These calibration images allowed the vertical position of moving particles to be determined accurately during the experiment.

The captured image sequences were analyzed using specialized image-processing software. Programs such as ImageJ, Origin, and MATLAB were used to determine particle trajectories, calculate velocities, and reconstruct three-dimensional flow patterns.

The recorded particle motion was then compared with the predictions obtained from numerical simulations. This comparison enabled verification of the theoretical model and provided a detailed understanding of how channel geometry affects AC electroosmotic flow.

Results and Discussion

The experiments clearly showed that the shape of the insulating channel has a strong influence on AC electroosmotic flow. Although the electrical operating conditions remained the same, changing the channel geometry produced noticeably different vortex structures. The experimental observations closely matched the predictions obtained from numerical simulations, confirming that channel shape is an effective parameter for controlling fluid motion inside microfluidic devices.

The movement of fluorescent particles provided direct evidence of the flow generated within the channels. Because the flow velocity was very low, the liquid remained in the laminar flow regime. Under these conditions, particle motion accurately represented the fluid movement, allowing detailed observation of the induced vortices.

The results indicate that modifying only the geometry of the insulating structure is sufficient to create different circulation patterns. This finding is important because it eliminates the need to redesign electrode configurations while still providing precise flow control.

Flow Visualization in the Parallelogram Channel

The parallelogram-shaped microchannel produced a stable and continuous vortex throughout the experiment. The suspended fluorescent particles followed a smooth circular path, indicating the presence of a single rotating flow inside the channel.

Three-dimensional particle tracking demonstrated that the particles moved upward and downward while simultaneously circulating along the channel. This confirmed that the vortex occupied the entire channel depth rather than being limited to the surface.

The observed particle trajectories agreed well with the theoretical predictions. The numerical model successfully predicted the direction and general shape of the vortex generated within the parallelogram geometry.

Another interesting observation was that particle velocity was not uniform throughout the channel. Near the acute corner, particles moved more rapidly, whereas lower velocities were observed near the obtuse corner. This variation reflects the influence of local electric field intensity created by the channel geometry.

Overall, the parallelogram design generated a simple and stable circulation pattern that can effectively improve mixing in microfluidic applications.

Flow Behavior in Channels with Non-Orthogonal Corners

The second channel design produced a significantly different flow structure. Instead of one continuous vortex, two separate vortices developed inside the channel.

This behavior occurred because the modified corner geometry changed the direction of the electric field lines. The flow generated near one corner interacted with the flow produced near the opposite corner, leading to the formation of two independent circulation zones.

Experimental images clearly showed that particles followed two distinct rotational paths. The numerical simulations predicted the same behavior, providing strong evidence that the proposed theoretical model accurately explains the influence of channel geometry.

The formation of multiple vortices is particularly useful in applications requiring rapid mixing because it increases interaction between different fluid layers.

Comparison Between Experimental and Numerical Results

A comparison between experimental observations and numerical simulations demonstrates excellent agreement. Both approaches predicted the same general flow characteristics for each channel geometry.

The theoretical model correctly explained the influence of acute and obtuse corners on fluid direction. Experimental particle trajectories closely followed the circulation patterns predicted by the simulations.

Small differences between the observed and predicted particle paths were mainly attributed to fabrication imperfections and unavoidable experimental limitations. Minor variations in channel wall angles, particle properties, and optical measurements may have contributed to these differences.

Despite these small deviations, the overall agreement confirms that the proposed numerical model provides a reliable method for predicting AC electroosmotic flow in channels with different insulating geometries.

Practical Significance of the Results

The findings of this study have important practical implications for microfluidic engineering. Instead of changing electrode arrangements, engineers can simply modify the insulating channel geometry to obtain the desired flow characteristics. This approach simplifies device fabrication while reducing manufacturing complexity and cost.

Conclusion

This study demonstrates that the geometry of insulating structures plays a major role in controlling AC electroosmotic flow inside microfluidic channels. Instead of modifying electrode configurations, the proposed method changes the cross-sectional shape of the channel to influence the local electric field distribution. Experimental observations and numerical simulations consistently show that different channel geometries produce different vortex patterns.

The parallelogram-shaped channel generated a single stable vortex, while the modified rectangular channel produced two separate vortices because of the presence of non-orthogonal corners. These observations confirm that channel geometry directly determines the direction and strength of electroosmotic circulation.

The agreement between theoretical predictions and experimental measurements validates the proposed design strategy. This simple approach provides an effective method for controlling fluid motion without increasing fabrication complexity.

The results also demonstrate that insulator-based flow control has considerable potential for improving mass transport, mixing efficiency, and particle manipulation in microfluidic devices. Such improvements are valuable for applications in biomedical diagnostics, chemical processing, environmental monitoring, and lab-on-a-chip technologies.

Future studies may investigate additional channel geometries, different operating frequencies, alternative insulating materials, and integration with advanced microfluidic systems to further enhance device performance.

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