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# A review on the application, simulation, and experiment of the electrokinetic mixers

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ABSTRACT

Electrokinetic driven flow can be used as an active technique to improve mixing in various devices. This technique is employed to mix fluid samples rapidly and efficiently in different geometries. There are numerous numerical and experimental studies on this subject in the literature. This paper is review of the studies performed on electrokinetic mixing techniques including electroosmosis, electrophoresis, and dielectrophoresis to discuss about capabilities, shortcomings, and various industrial and engineering applications of this method. Based on this survey, conclusions and suggestions for future works are provided.

## 1. Introduction

Fast-preparing a homogeneous mixture is necessary for many chemical and biological applications such as biological/chemical agent detection in microscale [31,70], lab-on-a-chip applications [13,4], drug delivery [33,53], DNA hybridization [93,14], PCR amplification [13,4], and so on. For some of these applications, the system has a micro-scale geometry which leads to a very slow mixing process mainly due to the laminar flow in these systems. Mixing in a laminar flow is only related to molecular diffusion. In absence of any turbulence, it is not possible to enhance the mixing simply by diffusion. Accordingly, a proper and innovative method is required to improve the mixing for such systems devices. In the literature, there are various passive and active methods employed to enhance the mixing processes in these micro-scale systems.

Passive methods are usually referred to the methods in which there is no need for external energy sources. In fact, they commonly are related to diffusion or chaotic advection employing a particular channel design that creates vorticities in the flow to increase the contact space and the contact time of species samples [87,56,6,27,5,26].

Aoki and Mae [6] investigated the effects of duct geometry on mixing index of micromixers employing collision of liquid segments as a passive technique. They enhanced the mixing index by increasing the flow rates and decreasing the duct sizes. Cortes-Quiroz et al. [27] investigated the design optimization of geometric specifications of a grooved micro-mixer as a passive device. They determined the best condition to achieve the maximum mixing index with minimum pressure loss. Ansari et al. [5] proposed a new design for a micro-mixer which creates vertical flow in a rectangular micro-mixer with tangentially aligned inlet ducts. They found that the vortex initially created at the inlet section of a rectangular micro-duct enhances the mixing action. They reported that this type of passive micro-mixer is easy to fabricate and controllable. In contrast to the passive methods, active methods employ an external energy source for disturbing the sample species. Some of the active techniques employed in the mixing process are using magnetic field [88,65], pressure disturbance [67], acoustic disturbance [102], vapor pneumatic power [94], etc.

Tsai and Lin [94] performed an experimental study on an active mixer driven by thermal bubble micropump. They used the oscillatory flow created by this micropump to induce wavy interface to increase the contact region of mixing fluids and consequently, improving the mixing index. Suzuki and Ho [88] used magnetic force to enhance the mixing of magnetics beads in bio-liquids. They found that the magnetic field created by the micro-conductors generates powerful attraction around the magnetic beads. Yaralioglu et al. [102] provided the mixing in a micro-mixer by employing an acoustic stirring generated by ultrasonic waves. They did not employ any moving parts in this micro-mixer. There is no need for complex structures in their micro-mixer. Ma et al. [67] designed a T-form micro-mixer driven by pressure disturbances as an active technique. They observed that as the best case, about 75% mixing is achieved within a distance of less than 3 mm from inlet of their micro-mixer.

It should be stated that generally, active methods used in mixing processes have a higher mixing index in comparison to the passive methods. Although it was mentioned the active methods effectively

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decrease the mixing time, most of them are integrated hardly into microfluidic systems. Moreover, using exterior variable-frequency drivers and interior mechanical movable components is necessary for them.

To overcome the above drawbacks, electrokinetic driven flow has been introduced as an active technique for enhancing the mixing process in various applications. Using this method in mixing systems has many advantages including miniaturization, negligible hydrodynamic dispersion, no moving components, simple design, fast and efficient mixing, no vibration and fatigue, electrical actuation, sensing, and facile integration with microelectronics [9]. Researchers used this technique for different applications [37,48]. Anderson [3] used this technique to transfer the colloidal particles with heterogeneous surfaces. Note that the particle transport has various applications in material or mineral processing, soil management, food science, cosmetics, paints and coatings, and so on. Nobari et al. [75] used this technique in a novel micro-pump. They employed the induced-charge electrokinetic flow to create vortices and a pressure gradient. This causes pumping the solution towards the outlet section of micro-pump. Rashidi et al. [82] reviewed applications of electrohydrodynamic method in different thermal energy systems. They reported that the pressure loss created by electrohydrodynamic method should be considered when evaluating this method for improving heat transfer rate. Lee et al. [58] reviewed active and passive mixers. They provided a comparison between the index of both active and passive mixers. These comparisons are presented for active and passive mixers in Tables 1 and 2, respectively. Mixing time, mixing length, and mixing index are provided as the key factors for each mixer in these tables. As presented in these tables, electrokinetic mixers have the highest mixing index among all active and passive mixers.

Electrokinetic mixing techniques including electroosmosis, electrophoresis, and dielectrophoresis play significant roles in mixing technologies. There are a large number of articles on this topic and many researchers have used this technique to improve mixing in various conditions. However, currently, there is no review paper specifically focused on this topic. Accordingly, the objective of this survey is to review all the studies performed in this field to discuss the, capabilities, shortcomings, and various industrial and engineering applications of this method.

## 2. Electrokinetic micromixers

Electrokinetic contains the phenomena where a liquid or particle moves tangentially to a charged surface. Electrokinetic techniques; including electroosmosis, electrophoresis, and dielectrophoresis, are very common in microfluidic systems. In this section, the studies on different types of electrokinetic micromixers including electroosmosis, electrophoresis, and dielectrophoresis micromixers are reviewed.

### 2.1. Electroosmosis micromixers

Electroosmosis shows the movement of the liquid under the influence of an imposed electrical field (Chen et al., 2003). Before discussing about electroosmosis mechanism, the electrical double layer should be defined. A schematic of electrical double layer is shown in Fig. 1. When a solid surface is in contact with a solution of an electrolyte, the electric charge (either positive or negative) is induced on the solid surface. This induced electric charge disrupts the electrolyte solution ions and adsorbs the opposite ions toward the surface. By increasing the concentration of opposite ions near the surface, a layer of these opposite ions is generated around the surface. This layer is called compact layer. Due to the attraction of the surface electric charge, the ions stick to the surface and are unmoved in the compact layer. As we move through the liquid away from the surface, there is a region where the concentration of anions and cations are equal together. The gap between the compact layer and this region is called the diffuse layer. In contrast with the compact layer, the ions are mobile in the diffuse layer. These two layers form a layer called as the electrical double layer. The interface between compact and diffuse layers is recognized as the surface of shear. By exerting an external electric field, the diffuse layer which has an intense electric potential moves along the duct. Accordingly, the diffuse layer pulls the liquid by drag force and causes enhancement in mixing process.

As a result, electrical double layer can be created around each object electrically non-conductive surface in contact with a solution of an electrolyte. When an external electric field is exerted, the negative and positive ions inside electrical double layer are moved towards the positive and negative sides of the electric field, respectively. These motions of ions drag their adjacent liquid molecules and accordingly, push the bulk liquid. This movement is recognized as electroosmotic flow. Fig. 2 discloses the electroosmotic around a non-conducting wall. Note that electroosmosis is based on the interaction of electrostatic charge at the liquid-solid interfaces with the externally imposed electrical field.

Some researchers used electroosmotic techniques to enhance the mixing in micro devices. Several techniques were proposed and investigated to manipulate and control the liquid motion and improve the mixing index in electroosmosis micromixers. Instability, employing voltage, surface charge patterns and heterogeneous surface, and placing obstacles are these techniques.

**Table 1**
A comparison between active mixers (Reprinted from Lee et al. [58]).

| Classification | Mixing method | Required time (ms) | Required length (μm) | Mixing index |
|---|---|---|---|---|
| Acoustic/Ultrasonic | Acoustically driven sidewall-trapped microbubbles | 120 | 650 | 0.025 |
| | Acoustic streaming created by surface acoustic wave | 600 | 10000 | 0.9 |
| Dielectrophoretic | Disordered advection related to Linked Twisted Map | ---- | 1000 | 0.85 |
| Electrokinetic time-pulsed | Disordered electric fields | 100 | Width*5 | 0.95 |
| | Periodic electroosmotic flow | ---- | 200 | 0.88 |
| EHD power | Staggered herringbone structure | ---- | 825 | 0.2 |
| | Staggered herringbone structure | ---- | 2300 | 0.5 |
| Thermal actuation | Thermal | ---- | 6000 | ---- |
| MHD flow | Large values of frequency | 1100 | 500 | 0.977 |
| Electrokinetic instability | Small values of Reynolds number | ---- | 1200 | 0.98 |