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Development of an enhanced MHD micromixer based on axial flow modulation

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ABSTRACT

A magneto-hydrodynamic (MHD) stirrer was analytically modeled, designed and experimentally tested. A novel modulation technique is presented which allows enhancing the mixing quality in a short amount of time. The stirrer was realized with two PCB layers and a glass cover; the channel presents electrodes posed on the bottom wall and on the sidewalls. All the electrodes are AC fed in order to avoid electrolysis and bubble formation during the stirring process. A fully programmable circuit allows creating vortices inside the mixing channel and to move the fluids with an oscillating motion from inlet to outlet; the electrodes on the bottom wall provide contra-rotating vortices and are fed with AC zero mean value square waves in-phase and in opposition of phase with respect to a magnetic field generated by an electromagnet. The sidewalls are fed by a modulated signal whose carrier is in phase with the magnetic field, while the modulant is a low frequency square wave with programmable frequency, amplitude, DC offset and duty-cycle; as an effect it is possible to make oscillate the fluid from inlet to outlet and enhance the stirring process by interaction of this axial oscillation with the contra-rotating vortices. Experimental efficiency of 90% can be reached in an amount of time of 24 s.

1. Introduction

Over the last decade, microfluidic devices have significantly emerged as a necessary tool for realization of micro total analysis systems (μTAS) or Laboratory-on-a-Chip (LoC) in different fields, such as biotechnology, chemistry, biomedicine, food and environment technologies [1–9].

Compared with traditional laboratory techniques, microfluidic systems offer smaller reagent volumes, a more rapid analysis, the possibility of parallel operation, and disposability. It is also possible to integrate an entire laboratory onto a single chip. Microdevices are capable of handling and analyzing fluids in structures of micrometer scale where, because of the small dimensions and low Reynolds numbers [10], laminar flow, diffusion, fluidic resistance and surface tension become dominant over turbulent flow and inertia. Compared to traditional reactors, with typical surface-to-volume ratios of $4\,m^2\,m^{-3}$, microfluidic systems are characterized by surface-to-volume ratios between $1000\,m^2\,m^{-3}$ and $30{,}000\,m^2\,m^{-3}$, with increased heat and mass transfer efficiencies.

Micromixer is the most important component in microfluidic systems. Since one consequence of laminar flow is that two or more streams flowing in contact with each other will not mix except by diffusion, it would take a long time and require a long microchannel to accomplish the mixing process if the channel is not very narrow, due to the dependence of the diffusion time on the square power of the distance.

For this reason, a great deal of attention has been given to the search for more efficient mixers in microfluidic systems with low Reynolds number and large Peclet number. In recent years, many researchers have analyzed stirrers by numerical methods [11–13] and have proposed different architectures of enhanced microfluidic mixing devices [14–20]. They can be classified into two main categories: active and passive ones. Passive ones have the advantage of no moving parts, labyrinths are created by posing particular walls geometries to enhance the stirring process and an external pumping device is required [21–24]. Because of the absence of active parts in them, they need longer paths with respect to active stirrers, this means that a longer amount of time in a greater area occupation is required to get well mixed fluids, at the same Reynolds numbers. Active stirrers can overcome these problems, but often an actuation with moving parts is required (e.g. piezoelectric); MHD mixers do not present moving parts, the actuation is given by electric and magnetic fields and there are no parts affected by consumption [16,25–29]. As it is known, some potential problems of MHD micromixers are bubble formation, electrode corrosion, and migration of analytes in the electric field. A solution to avoid bubble formation is presented in [30] where electrodes are AC driven with zero mean value. In the present work, a modulation technique is presented, which reduces electrolysis and, at the same time, provides a higher efficiency in a shorter time than previous works.

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In Section 2 the mathematical model of the electric current distribution in a channel having an electrode posed on the bottom wall and two sidewalls kept to ground potential is presented, giving analytical equations of the current density with comparison with the commercial FEM package COMSOL Multiphysics. In Section 3 the analytical prediction of the speed profile in a vortex generated by MHD force is presented, with comparison with FEM simulations. In Section 4 the design and realization of the stirrer is presented. In Section 5 the modulation technique with the circuit description and realization is presented. Finally in Section 6 the experimental results with qualitative and quantitative analysis of the stirrer performances is presented.

2. Theory of operation: electrostatics

The force per unit volume provided to a conductive fluid posed in a magnetic field $\bar{B}$ and flown by an electric current density $\bar{J}$ is

$$\overline{f_{MHD}} = \bar{J} \times \bar{B}. \tag{1}$$

Considering a constant magnetic field directed along the z direction $\bar{B} = B_0\hat{z}$ then the force in (1) will have components only in the x and y directions. The aim of this section is to study the electric current density distribution inside the channel when an electrode is posed on the bottom wall at potential V_0 and the sidewalls are kept to ground in order to predict the velocity field of the fluid during the stirring process.

In Fig. 1 a cross section of the channel is shown and the analytical study below will refer to this 2D section posed in the center of the electrode along the x direction. Since $\bar{J} = \sigma\bar{E}$ and $\bar{E} = -\nabla V$, being σ the electrical conductivity of the fluid, $\bar{E}$ the electric field and V the electric potential, it is possible to describe the current density studying the electric potential distribution inside the cross section. The solution of the problem must be searched via the separation of the variables, i.e. posing $V(y,z) = f(y)g(z)$. Non-uniformity of electrolytes concentration can occur nearby the electrodes in a double-layer zone but, in quasi steady state conditions, the relaxation time ε/σ of the liquid is negligible and the ions can equilibrate locally so that the bulk electrolyte behaves in a resistive manner [31]; then the electrical potential satisfies Laplace's equation $\nabla^2 V = 0$ and the solution is in the form

$$V(y,z) \propto e^{-\beta(y+\imath z)}, \tag{2}$$

where the boundary conditions $V(-W,z) = V(W,z) = 0$ bring to $\beta = n\pi/2W$. Boundary potentials are known on the electrode, while $V(y,0)$ has to be determined for $W/2 < |y| \le W$; the potential on these boundaries can be obtained considering the image charge method and posing three punctual charges respectively in $(y,z) = \{(0,0); (-2W,0); (2W,0)\}$ whose charge values can satisfy $V(-W/2,0) = V(W/2,0) = V_0$ in order to obtain the potential continuity. Under these conditions the potential on the boundaries is

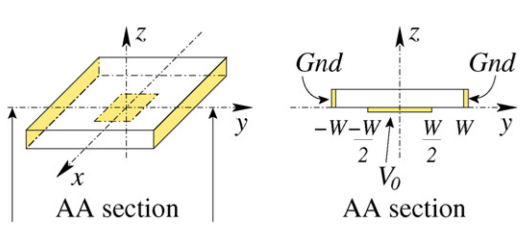

Fig. 1. Schematic view of the geometry to be studied: disposition of the electrode (left) and cross section with boundary conditions (right).

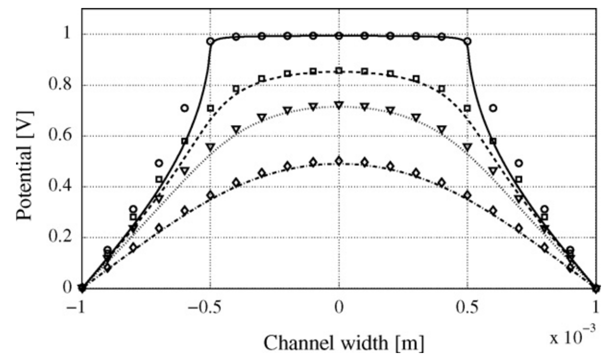

Fig. 2. Electric potential distribution inside the channel: 50 μm height (–, ○); 125 μm height (- -, □); 250 μm height (···, ▽); 500 μm height (-·-, ◊). Lines refer to simulations, markers to theoretic values.

defined as

$$V(y,0) = \begin{cases} \dfrac{-3V_0W}{4}\left(\dfrac{1}{y} + \dfrac{1}{y+2W}\right) & -W \le y < -\dfrac{W}{2} \\ V_0 & -\dfrac{W}{2} \le y \le +\dfrac{W}{2} \\ \dfrac{3V_0W}{4}\left(\dfrac{1}{y} + \dfrac{1}{y-2W}\right) & +\dfrac{W}{2} < y \le +W \end{cases} \tag{3}$$

and the solution inside the channel is the Fourier series

$$V(y,z) = \sum_{n=1,3,5,\ldots}^{+\infty} A_n \cos\left(\frac{n\pi y}{2W}\right) e^{-n\pi z/2W} \tag{4}$$

where

$$A_n = \frac{V_0}{2W}\int_{-W}^{+W} V(y,0)\cos\left(\frac{n\pi y}{2W}\right) dy$$
$$= V_0\left[\frac{3}{2}\mathrm{Ci}\left(\frac{3n\pi}{4}\right) - \frac{3}{2}\mathrm{Ci}\left(\frac{n\pi}{4}\right) + \frac{4}{n\pi}\sin\left(\frac{n\pi}{4}\right)\right], \tag{5}$$

being Ci the cosine integral function [32]. Maxwell equation states that

$$\bar{J} = \sigma\bar{E} + \frac{\partial\bar{D}}{\partial t} \tag{6}$$

where the second term $\partial\bar{D}/\partial t$ is related to the absence of electroneutrality when the electrolyte concentration is not uniform. In steady-state and slowly time varying analysis, $\partial\bar{D}/\partial t \approx 0$ and, consequently, the current density which moves the fluid is

$$J_y(y,z) \approx -\sigma\frac{dV}{dy} = \sum_{n=1,3,5,\ldots}^{+\infty}\left(\frac{\sigma n\pi A_n}{2W}\right)\sin\left(\frac{n\pi y}{2W}\right) e^{-n\pi z/2W} \tag{7}$$

Numerical computation of (4) has shown that truncating the sum at order $n = 35$ provides less than 1% error with respect to a quasi-infinite order; differently (7) has to be truncated at order $n = 155$ because of the presence of n at numerator. In order to verify equations presented above, a 2 mm wide and 500 μm high channel has been simulated using a FEM software posing an electrode 1 mm wide at potential 1 V.

Fig. 2 shows the comparison between simulated (lines) and theoretical (markers) electric potential $V(y,z)$ at $z = 50$ μm, 125 μm, 250 μm and 500 μm, respectively. Fig. 3 points out the excellent agreement in the electric field $E_y(y,z)$ between FEM simulations (lines) and theoretical analysis (markers) at $z = 50$ μm, 125 μm, 250 μm and 500 μm.