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Experimental characterization of the fluid flow induced in micro chambers by redox-magnetohydrodynamic pumping

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Abstract

The fluid flow induced by MHD-pumping with immobilized redox species has been experimentally investigated applying astigmatism particle tracking velocimetry (APTV). With this technique, velocity fields induced between two, coplanar band-electrodes coated with PEDOT were analyzed in detail by volumetric three-component flow measurements. It was found that the fluid flow in stream-wise direction scales with the Lorentz-force density, while no significant velocity component in height-direction exists. The velocity field exhibits a flat and parabolic velocity profile at the horizontal and vertical centerlines, respectively. Because viscous forces dominate, the parabolic velocity profile remains when the ratio of the distance between the electrodes and chamber height is about 2, at which a significant uneven distribution of the Lorentz-force density is expected.

Introduction

Lab-on-a-chip systems require pumping and mixing of small amounts of liquids or tailored transport of biological samples, for which several methods based on electric, acoustic or magnetic fields are often exploited (Squires and Quake 2005). Among others, Redox-magnetohydrodynamics (R-MHD) is a unique approach to drive fluid flow in lab-on-a-chip systems, and offers several features that either complement or improve upon other microfluidic pumping methods, including a flat horizontal velocity profile, low voltage requirements, portability and programmability (Sahore and Fritsch 2013). In addition, this method is capable of performing multiple, parallel chemical analysis without requiring independent channels (Sahore and Fritsch 2014). In MHD, fluid flow is induced by the Lorentz-force ($\mathbf{F_L}$) resulting from a net ionic current density ($\mathbf{j}$) in the solution in the presence of a magnetic flux density ($\mathbf{B}$), by following the equation $\mathbf{F_L} = \mathbf{j} \times \mathbf{B}$. The ionic current can be generated between the electrodes in a solution by applying an electrical current or potential to oxidize and reduce electroactive (redox) species. Redox species can be confined to the electrode surface or mixed with electrolyte solution. However, the latter may produce interference with analytes (Nash and Fritsch 2016). The advantage of immobilized redox species is that of an easily-accessible, high concentration of charge at the electrodes that offers high current densities, and therefore high fluid velocities. For this, the conducting polymer PEDOT (Poly(3,4-ethylenedioxythiophene) deposited onto the electrode surfaces can be used for MHD pumping, while maintaining good chemical stability, reversible doping states, and low redox potential (Nash and Fritsch 2016). The pumping efficiency, expressed as the ratio between velocity and duration of the pumping depends not only on the current density and the available charge capacity that can be optimized by the thickness and morphology of the polymer film (Khan and Fritsch 2016), but also on the geometrical dimensions of the setup, given by the actual chip design and the height of the chamber used to transport electrolyte solution inside.

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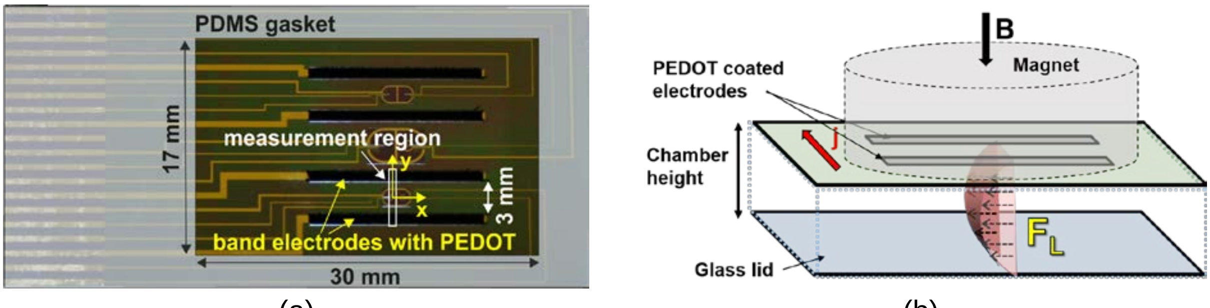
In order to investigate the influence of the latter, three-dimensional measurements of the fluid flow were carried out for different experimental parameters, e.g. chamber height and different electronic currents. In this way, the fluid flow induced in between parallel band-electrodes modified with PEDOT can be assessed experimentally, revealing characteristics of the fluid flow that inherently exist and may correlate with the spatial distribution of the Lorentz-force.

Experimental setup

In order to experimentally investigate the fluid flow induced by MHD pumping with immobilized redox species, a chip design very similar to that used in (Nash and Fritsch 2016) was utilized. The chip is depicted in Figure 1(a). It consists of parallel micro band-electrodes made of gold, comprising four electrodes of 100 nm thickness, 650 µm width and 15 mm length, with a gap in between the outer pairs of 3.2 mm and for the inner pair of 4.7 mm. These electrodes were coated with PEDOT via electrochemical deposition with optimized parameters to obtain well-adherent polymer films of (28 ± 3) µm in thickness (appears black on top of the gold electrodes). The horizontal distance between the electrodes that were activated to produce MHD flow amounts to 3.2 mm. A Polydimethylsiloxane (PDMS) gasket with an opening of about 30 mm x 17 mm was placed over the chip to define the chamber. The volume of the chamber ranged between 0.22 mL and 0.85 mL, depending on the actual height of the three different PDMS gaskets used for the present experiments. As electrolyte, a sodium chloride solution with a concentration of 0.1 M was chosen, in which glycerol of about 20 wt% was added, yielding a density of the solution of about 1.05 g/cm^3. In that way, the density of the particles used for flow measurements matched that of the electrolyte, avoiding sedimentation of these particles. A thin glass coverslip was placed over the gasket to serve as a lid and provide optical access for the flow measurements. For this, the assembled chamber was put upside down on an inverted epi-fluorescent microscope (AxioObserver 7, Zeiss). A neodymium−iron−boron (NdFeB, Amazing magnets LLC) permanent magnet (35 mm in diameter and 12.7 mm in thickness, magnetic flux density at the surface of about 0.37 T) was placed on top to provide a magnetic field perpendicular to the chip, see the sketch of the setup in Figure 1(b). To pump the fluid in between both parallel electrodes via Lorentz-force, an ionic current crossing from one band to the other was generated by applying a constant electronic current for a certain time, having a duration that depended on the charge capacity of the PEDOT. The current applied to the electrodes ranged between 100 mA and 400 mA for the measurements.



(a) (b)

Figure 1: (a) Chip with parallel band-electrodes coated with PEDOT. The measurement region is located far away from the end of the electrodes and PDMS gasket side-walls. (b) Sketch of the assembled setup, in which fluid flow is induced by R-MHD due to the superposition of a magnetic field by placing a permanent magnet directly behind the chip.

In order to measure the three-component, three-dimensional (3C3D) fluid flow astigmatism particle tracking velocimetry (APTV, Cierpka et al. 2010) was utilized, for which monodisperse, fluorescently labeled polystyrene particles (ex/em: 540/607 nm, MicroParticles GmbH) with a diameter of 5 µm and a density of about 1.05 g/cm^3 were added to the electrolyte. A green, high-power LED (SOLIS-525C, Thorlabs) was used as light source. The light emitted from the particles was observed with a microscope objective (LD Plan-Neofluar, 20x/0.4, Zeiss) and captured by a monochrome camera (Imager sCMOS, LaVision GmbH) operating in single-frame mode. Astigmatic particle images were obtained by placing a cylindrical lens with a focal length of 200 mm in front of the camera. The pulse width of the LED and frame rate of the camera were adjusted prior to each measurement in order to obtain particle images suitable for particle tracking at each individual parameter setting, e.g. current density applied. With the optical setup, the measurement volume of the APTV amounted to approximately (w_x x w_y x w_z) = (680 x 1050 x 80) µm in size. As the distance between the parallel electrodes was 3.2 mm and the height of the chamber amounted to 430 µm, 860 µm or 1680 µm, depending on the PDMS-gasket used, measurements were conducted at several positions inside the chamber to cover the entire measurement region marked in Figure 1(a). In order to get an overlap between the measurement positions, the measurement volume was traversed through the region of interest with a step width of 500 µm in the *y*-direction and of about 40 µm in the *z*-direction. No traversing in the *x*-direction was needed as no change of the velocity field in streamwise-direction occurs for the chosen measurement position close to the center of the length of the parallel electrodes. There, a fully-developed laminar flow is expected within a very short starting time (< 1 s). However, the charge capacity of the PEDOT-film limited the pumping duration to 30 s for the highest applied current of 400 µA. Therefore, the PEDOT had to be recharged after each measurement by applying a reversed current of the same magnitude and duration, which resulted in an opposite directional fluid flow, due to having a constant magnetic field direction throughout the whole experiment. During this time, velocity measurements were conducted as well, allowing to check for differences between both current directions that should ideally not occur. Additionally, the total number of measurements can be increased by taking a reversal of the fluid flow into account. For all measurements, the in situ calibration approach was used to obtain physical coordinates of the particles, see Cierpka et al. 2011.

Results

The *u*-component of the velocity field that had been obtained within the chosen measurement region is depicted in Figure 2. For this, all detected and valid particles were tracked between consecutive particle image captures using a nearest neighbor approach.

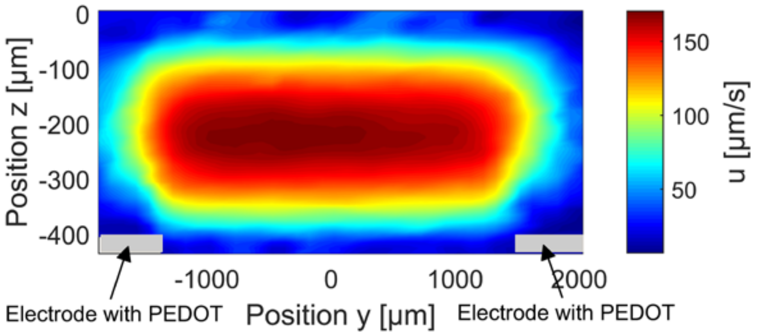


Figure 2: *u*-component of the velocity field in between the parallel band-electrodes for an applied current of 400 µA and chamber height of about 430 µm.

Afterwards, the randomly distributed particle velocity vectors were ensemble-averaged and interpolated onto a rectangular grid using Gaussian-weighted interpolation based on the vector distance from the grid nodes. The size and the overlap between neighboring bins was set to (Δy x Δz) = (200 x 10) µm² and 50%, respectively. Hence, while the width w_x of the measurement volume determines the spatial resolution in stream-wise direction, the grid spacing in span-wise direction amounted to 100 µm in *y*-direction and 5 µm in *z*-direction. As can be seen in Figure 2, an almost symmetrical velocity field exists between the electrodes coated with PEDOT. The centerline velocity profiles depicted in Figure 3 clearly confirm the symmetrical characteristic.

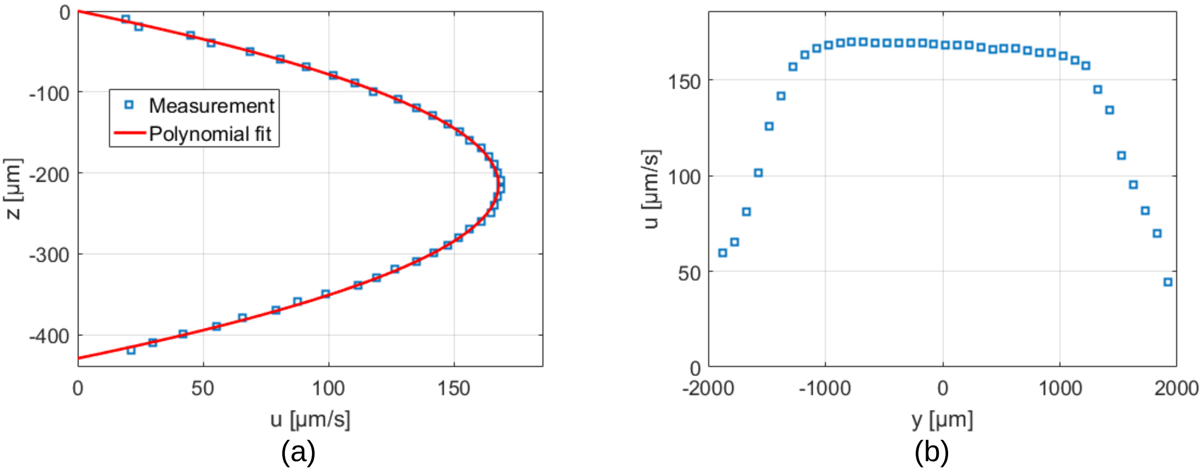


Figure 3: (a) vertical and (b) horizontal centerline velocity profile for a current of 400 µA and a PDMS gasket height of about 430 µm.

While a parabolic velocity profile occurs near the center in height-direction, see Figure **3**(a), the horizontal centerline velocity profile exhibits a flat profile, see Figure **3**(b). In addition, no significant velocity occurs in the *y*- and *z*-directions (not depicted here). Such flow characteristic reminiscent of a pressure-driven flow in rectangular microchannels of high aspect ratio of width to height of those channels. However, in contrast to a pressure-driven flow no channel sidewalls are needed here. The flow rate can be easily adjusted by increasing the current density, and as expected for MHD pumping the velocity induced by the Lorentz-force is also directly proportional to the current density applied, as can be seen for the corresponding magnitude of the velocity profiles depicted in Figure 4(a). Furthermore, the general flow characteristics do not change with increasing height of the PDMS chamber. This means that while the magnitude of the velocity increases due to a lower hydrodynamic resistance, the velocity profile near the center remains parabolic-like, even though the ratio of the distance between the electrodes and the chamber height is smaller than 2. This can be clearly seen in Figure 4(b), where the centerline velocity profile in height-direction is depicted for the three different gasket heights at a constant current of 400 µA.

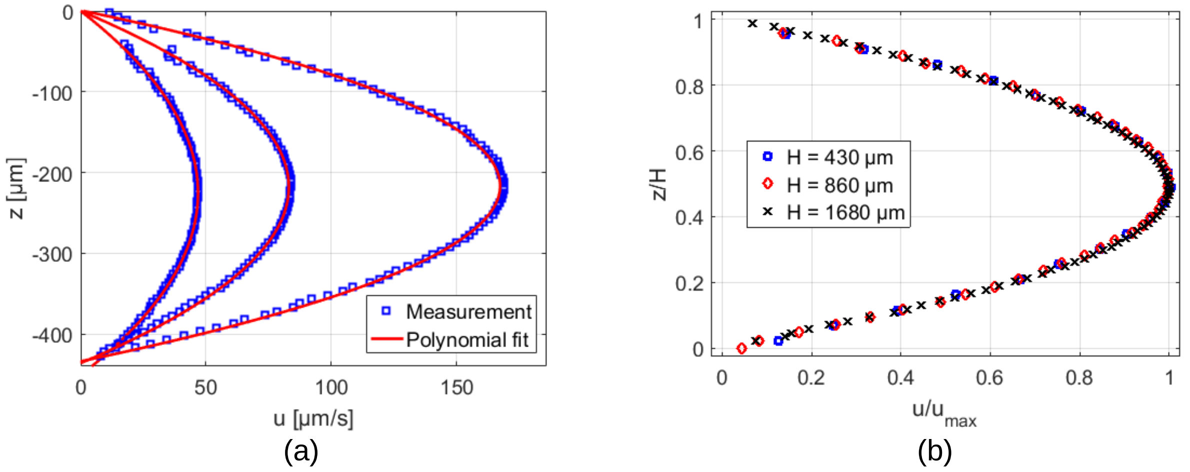


Figure 4: Centerline velocity profile in *z*-direction for (a) three different currents using a PDMS chamber of about 430 µm in height and (b) three different chamber heights at a current of 400 µA. For better comparison the velocity profiles were normalized with respect to the chamber height and maximum velocity. The chip with the electrodes is located at position -430 µm and 0 in (a) and (b), respectively.

Conclusions

In order to experimentally characterize the fluid flow induced in a micro chamber by redox-magnetohydrodynamic pumping, astigmatism particle tracking velocimetry was applied for the first time. In this way, velocity fields induced between two parallel band-electrodes coated with PEDOT could be analyzed in detail by delivering volumetric three-component flow velocity measurements. It was found that the fluid flow in stream-wise direction scales with the Lorentz-force density as expected, while no significant velocity component in height-direction exists. The measured velocity field is reminiscent of a pressure-driven flow in rectangular microchannels of high aspect ratio. Also, flat horizontal velocity profiles of different velocities can be induced just by varying the current density. Recently, this feature has allowed the R-MHD pumping approach to be used for biological applications employing image cytometry (Khan et al. 2018). In contrast to the pressure-driven flow no channel walls are needed. Furthermore, the vertical velocity profile in the center of both electrodes remained almost perfectly parabolic for three different ratios of the distance between the electrodes and the height of the PDMS chamber. Only for the largest ratio of about 2, a very slight tilt of the velocity profile towards the chip with the electrodes exists. This indicates that the fluid flow induced by the Lorentz-force is dominated by viscous forces as the velocity profile does not reflect the uneven distribution of the Lorentz-force density within the cross-section of the measurement region. The Reynolds-number that was $Re \leq 1$ for the present experiments confirms this result. In order to experimentally elaborate on the correlation between Lorentz-force and velocity distribution, further flow measurements were carried out at setups using a smaller ratio of the distance between the electrodes and chamber height as well as at higher Reynolds-numbers. These results will be presented and discussed at the conference.

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