The Effects of Joule Heating on Electric-Driven Microfluidic Flow

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This study sought out to more clearly understand the relationship between Joule heating and fluid flow in microfluidic environments, and more specifically, under what circumstances would the fluid flow in the device possibly hinder an experiment being run on it. It had been previous theorised that an electric field may produce turbulence and even vortices within the fluid, which this study attempted to reproduce. Several variables were tested, namely insulating and conducting fluids, higher and lower AC voltages, Newtonian vs. non-Newtonian fluids, and higher and lower DC voltages. A correlation between these variables and turbulent flow was found, with more conductive fluids, higher AC voltages, non-Newtonian fluids, and higher DC voltages more prone to fluid turbulence.

Introduction

Lab-on-a-chip devices are widely used in research to perform microfluidic chemical and biomedical analysis. However, some of these chips are driven using an electric field, which can cause potentially catastrophic side-effects, one of which is joule heating. Joule heating is an effect where heat is produced in a medium through which an electric current is passed. This can be an issue in microfluidic devices, especially in those with designs that contain constrictions in their channels. Due to the fact that electrical resistance increases with decreasing cross-sectional area and more heat is produce when resistance increases, temperature gradients can form in the fluid. This creates chaotic flow that may disrupt any experiment being performed on the chip.

Two prior studies on insulator-based dielectrophoresis (Sridharan, Zhu, Hu, & Xuan, 2011) and reservoir-based dielectrophoresis (Kale, Patel, Qian, Hu, & Xuan, 2013) have been done to try and understand this phenomenon, although their focuses were far more narrow. This study sought to expand on previous results and to test more variables that may influence the fluid flow. In our experiment, we observed how Joule heating affected fluid flow with varying applied AC voltage, electrical conductivity, condition of Newtonian versus non-Newtonian fluid, and applied DC voltage.

Methods

Lab-on-a-chip devices are manufactured in a complex and lengthy process, divided into three parts: master fabrication, copying, and testing. Before the master copy was fabricated, SU-8-25 photoresist was obtained, glass slides were soaked in individual bottles filled with acetone, two rinsing bottles were filled with deionised (DI) water and isopropanol, and the desired photomask for the microchannel was attached to a glass slide and placed in a petri dish. Two hot plates were heated to 65°C and 150°C, respectively.

After letting the glass slides soak, two slides were transferred into one acetone bottle, which was placed in a Branson 2510 Ultrasonic Cleaner for 5 minutes. The glass slides were then removed from the bottle, rinsed thoroughly with DI water, then blasted with pressurised nitrogen to remove water droplets. The slides were baked at 150°C for 10 minutes to fully dehydrate. The slides were removed from the hot plate and placed on clean tissue paper. This process is reused in copying, and therefore will be referred to as slide preparation.

Next, a slide was placed in the middle of a spin coater. Using a syringe, about 3mL of photoresist was drawn up, and 1.5 mL to 2 mL was dispensed onto the slide with constant flow and in a spiral motion to prevent bubbles. After closing the lid, nitrogen gas was pumped into the spin coater and the vacuum pump was turned on, keeping pressure at 60 to 80 psi. The spin coater spun the slide, accelerating to 500 rpm over five seconds, then accelerating to 2000 rpm over another five seconds, then holding at 2000 rpm over 30 seconds. This spin process produced a 25 µm thick film of photoresist. After spinning, the slide was removed and baked at 65°C for four minutes and then at 95°C for 8 minutes.

After the slides cooled, the coated slide was placed photoresist-side-up under the slide with the photomask attached, photomask-side-down. Another clean glass slide was placed on top, and the arrangement was squeezed tightly. The photoresist was then exposed under ultraviolet light. The photoresist slide was then removed and baked at 65°C for two minutes and then 95°C for four minutes. After it had cooled, the slide was immersed in a bottle filled with developer solution and gently shaken for four minutes. The slide was rinsed with DI water, then briefly with isopropanol. The slide was dried with a gentle stream of nitrogen, then baked again at 65°C for one minute and 95°C for five minutes. After cooling, the slide was placed in a petri dish for copying.

To fill the petri dish for the first time, Sylgard 184 silicone elastomer kit was obtained. A total of 18 mL elastomer and curing agent was dispensed into a separate petri dish in a 10:1 ratio. The poly(dimethysiloxane), or PDMS, mixture was stirred for four minutes, then poured into the petri dish containing the master. That petri dish was placed into a vacuum oven and kept at -20 mmHg for 15 minutes to remove air bubbles. The petri dish was then placed in a gravity convection oven for a minimum of three hours at 70°C to cure, although overnight was preferable.

After curing, two slides were prepared. Using a clean scalpel, a microchannel was cut out of the PDMS in which the master lies. This PDMS chip was placed on one of the slides, channel-side-down. Holes for the reservoirs were then cut out of the chip. The chip was then turned over and elevated from the slide with the cut out holes. Both slides were placed side-by-side into a PDC-32G plasma cleaner and sealed in. Using a vacuum pump, air was evacuated for two minutes, after which the power was turned on. After waiting 20 seconds, the knob was turned to "High". Immediately afterward, the valve on the front seal was turned until the plasma inside was brightest. This was left for 30 seconds, after which the plasma cleaner was turned off and the slides removed. The PDMS chip was immediately turned over and placed channel-side-down onto the unused slide. If the chip did not fully bond, tweezers were used to press gently on the chip until it was sufficiently bonded. Before testing, a drop of DI water was placed into one of the reservoirs in the channel and drawn via improvised vacuum (in this case, a syringe with an attachment) to the opposite reservoir. The water was removed with a pipette.

Many solutions were prepared for this experiment, in which the two main variables were phosphate buffer and poly-ethylene oxide (PEO) concentration. Solutions were prepared with 0.01mM, 0.1mM, 1mM, and 5mM buffer concentrations, initially containing no PEO. Later, similar solutions containing 1000 ppm PEO were also prepared. 0.5 µm fluorescent polystyrene particles were added to visualise the fluid flow, and a 1:10 volume ratio of TWEEN 20 was added to keep the particles from adhering to the channel walls. These solutions were tested in the chips, which were hooked up via electrodes to an Agilent LXI 33220A 20 MHz Function / Arbitrary Waveform Generator running through a TRek Model 609E-6 High Voltage Amplifier at 1000x amplification. The particle flow was observed under a Nikon Eclipse TE2000-U inverted microscope with an attached Nikon Digital Sight DS-Qi1Mc CCD camera and Nikon Intensilight C-HGFI fluorescent light. The images shown in the results section were created by initially taking a short video of the experiment, then using software to overlay each frame. This allowed the visualisation of the flow path of each particle in the solution, which when viewed as a whole, revealed the flow lines along that section of microchannel.

Results

The 0.1mM buffer solution produced turbulence around the constriction at 400V (Figure 3), and weak, poorly defined vortices at 450V (Figure 4).

The solution containing 1mM phosphate buffer produced clearly defined vortices at 400V. Vortex size increased at 450V.

The 5mM buffer solution produced small vortices starting at 250V *(Figure 10)*. These increased in size and started to disrupt normal fluid flow outside of the constriction as well, creating secondary vortices above 400V *(Figure 12)*.

The solution containing 1000ppm poly(ethylene oxide) and 0.1mM buffer produced turbulence inside the constriction starting at 300V AC (Figure 14). This effect increased at 400V (Figure 15) and 450V AC (Figure 16). At 200V DC (Figure 19), very small but violent vortices appeared around the corners of the constriction, and mild turbulence was observed throughout the channel. This effect was increased at 300V DC (Figure 20), and a large amount of turbulence was observed.

This solution contained 1000ppm PEO and 1mM buffer. Mild turbulence was observed at 300V AC (Figure 22). Strong turbulence was observed at 400V (Figure 23) and 450V AC (Figure 24). Very small vortices appeared at 450V AC as well, increasing in size at 500V (Figure 25). At 200V DC (Figure 26), some turbulence was observed just before and after the constriction. At 300V DC (Figure 27), turbulence increased dramatically, and the same small vortices around the corners of the constriction began to form.

Inducing a large electric field in the microchannel would eventually burn it (Figure 28). The effect was cumulative over time, although the time required to burn the channel decreased significantly with voltages of 500V or more. Initially, the only symptom of a burned channel were small bubbles surrounding the constriction. With excessive voltage input however, the bubbles would rapidly increase in number, the constriction would collapse, and the solution would produce large gas bubbles that moved about turbulently.

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Discussion

From the pictures above, several correlations and causations can be determined. The main conclusion is that the electrical conductivity of the solution directly correlates with the size of vortices formed by Joule heating. At 450V AC, the vortex in the 0.1mM buffer solution is weak (Figure 3). However, the same voltage in the 5mM buffer solution produces much larger vortices, strong enough to create secondary vortices not caused by Joule heating but simply by the flow of the inner vortices (Figure 13).

In addition, the conductivity of the solution inversely correlates with the AC voltage required to form a vortex. At 0.1mM buffer concentration, a weak vortex forms around 400V AC (Figure 3). However, at 5mM buffer concentration, vortices form as low as 250V (Figure 10).

An increase in supplied AC voltage also causes an increase in vortex size. In the 5mM buffer solution, the vortices at 250V AC are small (Figure 10). At 300V (Figure 11), the vortices are larger, and at 400V (Figure 12), they are strong enough to produce their own secondary vortices.

Furthermore, the introduction of PEO to create a non-Newtonian fluid causes a more turbulent flow, as shown in Figures 14-17 and 21-25. Without PEO in solution, the flow inside the constriction is very laminar. However, the flow is much more turbulent inside and around the constriction with PEO.

Finally, an increase in supplied DC voltage (when PEO is in solution and AC voltage is turned off) causes an increase in flow rate, which then causes an increase in turbulence around the constriction. With 10V DC applied, flow rate is low and fluid strain around the constriction is relatively low. With 100V or more (Figures 18-20, 26, 27), flow rate is high, fluid stress is high, and strain is much higher.

For further directions in this line of research, some options could be to observe the effects in the aforementioned conditions more clearly and quantitatively or test other types of fluids or channel designs to see how those variables affect the fluid flow.

Acknowledgements

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Notes and References

Kale, A., Patel, S., Qian, S., Hu, Q., Xuan, X. (2013). Joule heating effects on reservoir-based dielectrophoresis. *Electrophoresis 2014*, 721-727.

Sridharam, S., Zhu, J., Hu, Q., Xuan, X. (2011). Joule heating effects on electroosmotic flow in insulator-based dielectrophoresis. *Electrophoresis 2011*, 2274-2281.

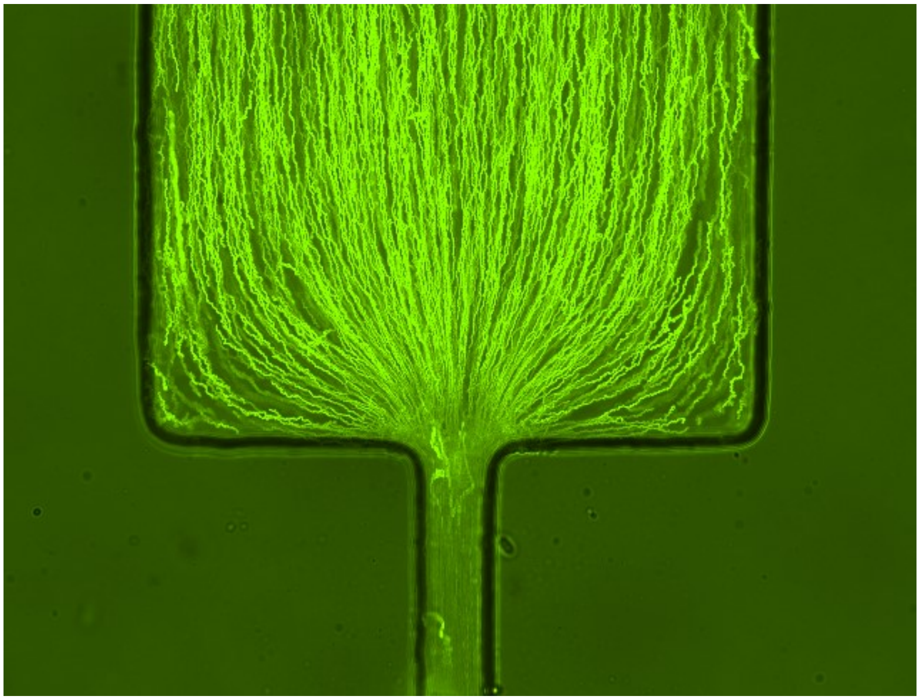

Figure 1 Solution contained 0.1mM buffer, AC set to 200V, DC set to 10V

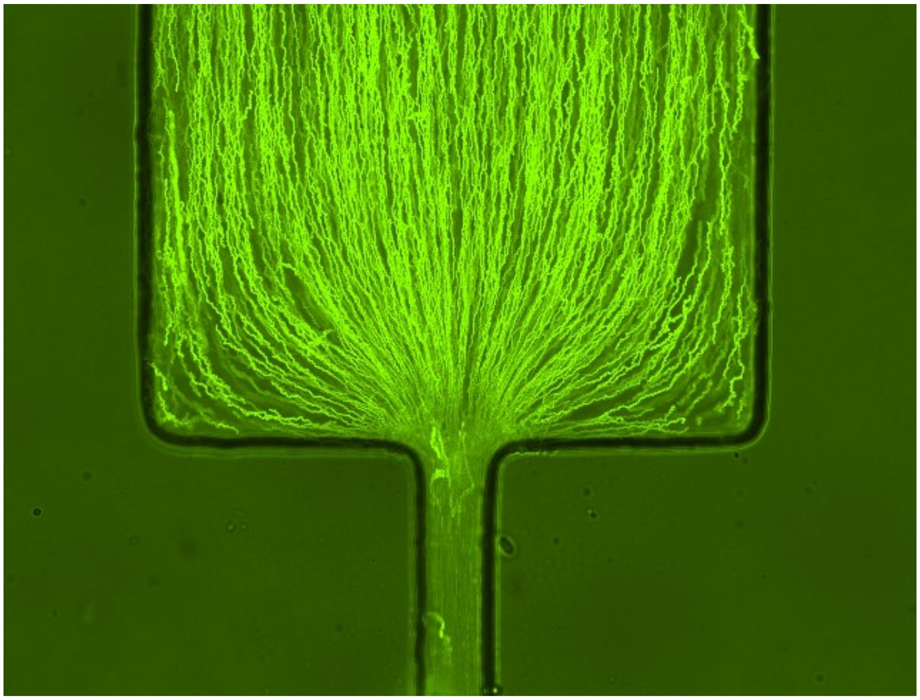

Figure 2 AC increased to 300V

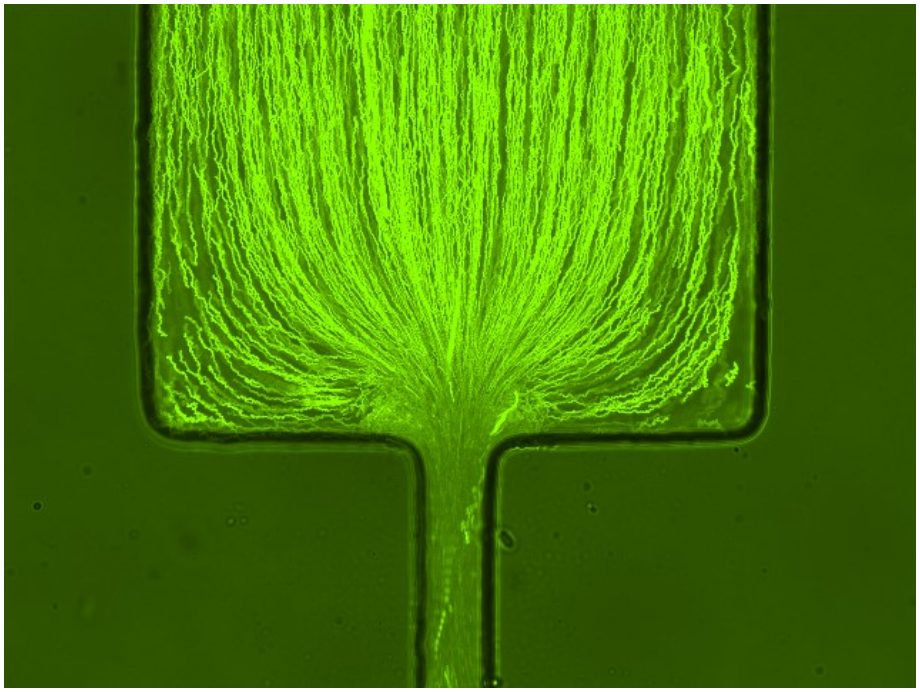

Figure 3 AC increased to 400V

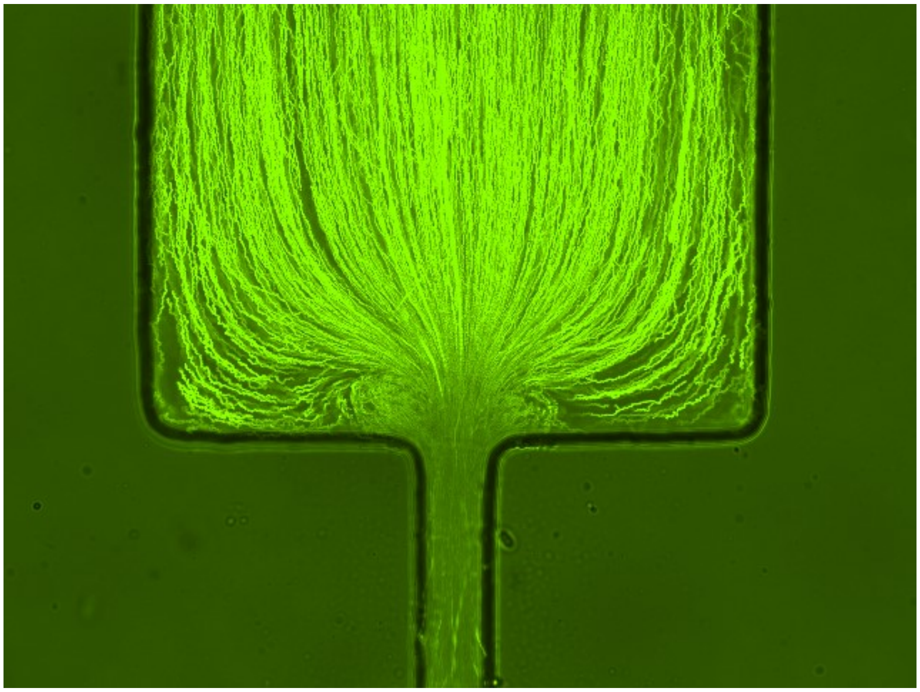

Figure 4 AC increased to 450V

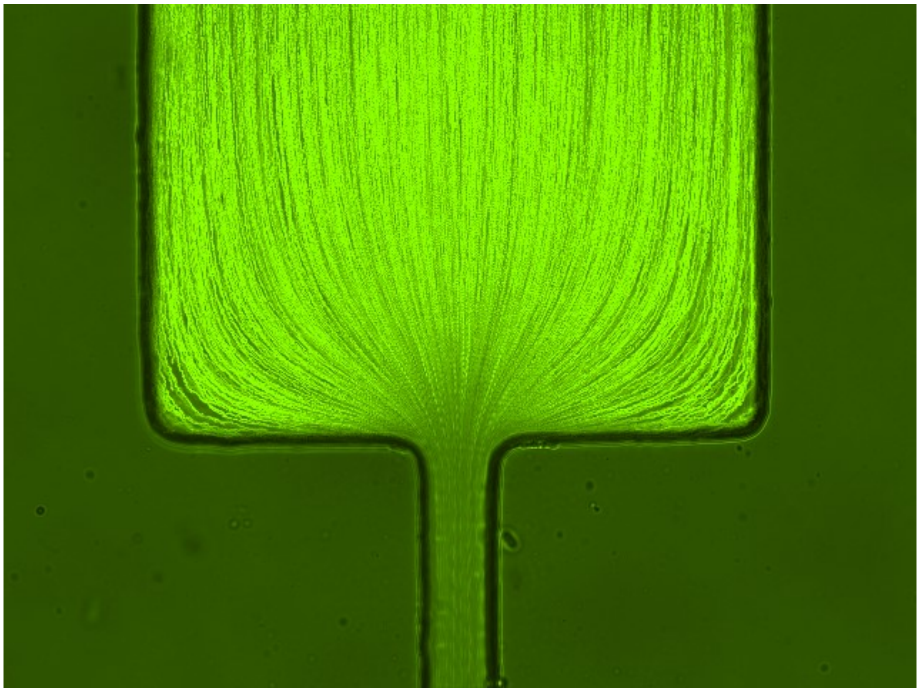

Figure 5 Solution contained 1mM buffer, AC set to 200V, DC set to 10V

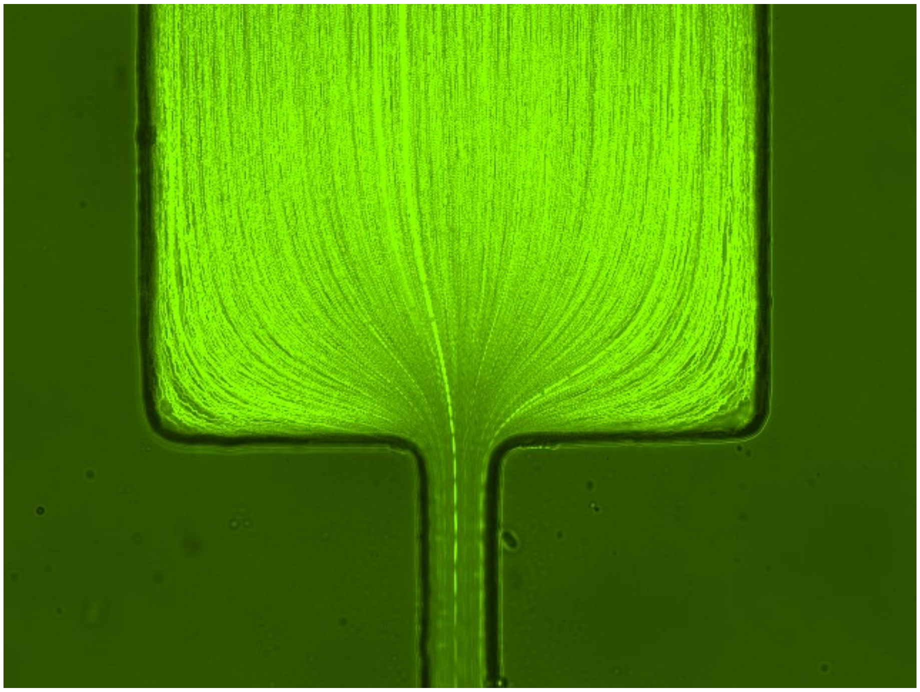

Figure 6 AC increased to 300V

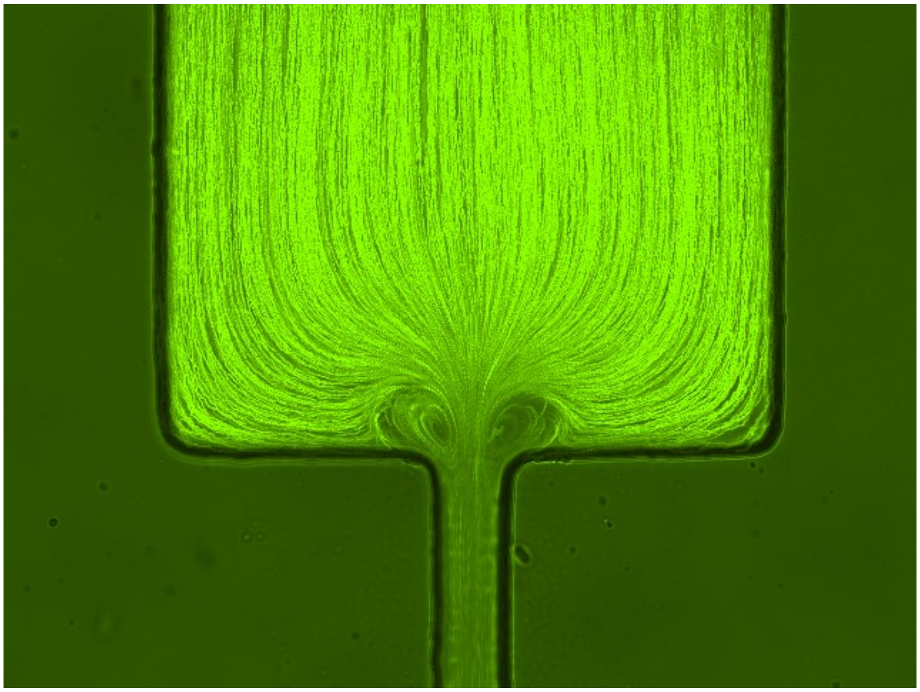

Figure 7 AC increased to 400V

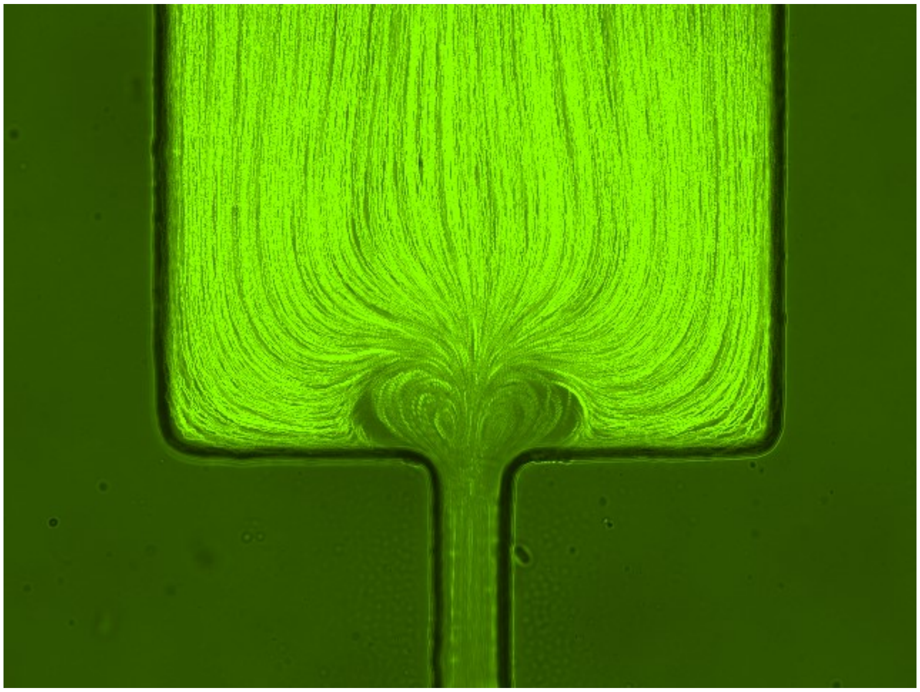

Figure 8 AC increased to 450V

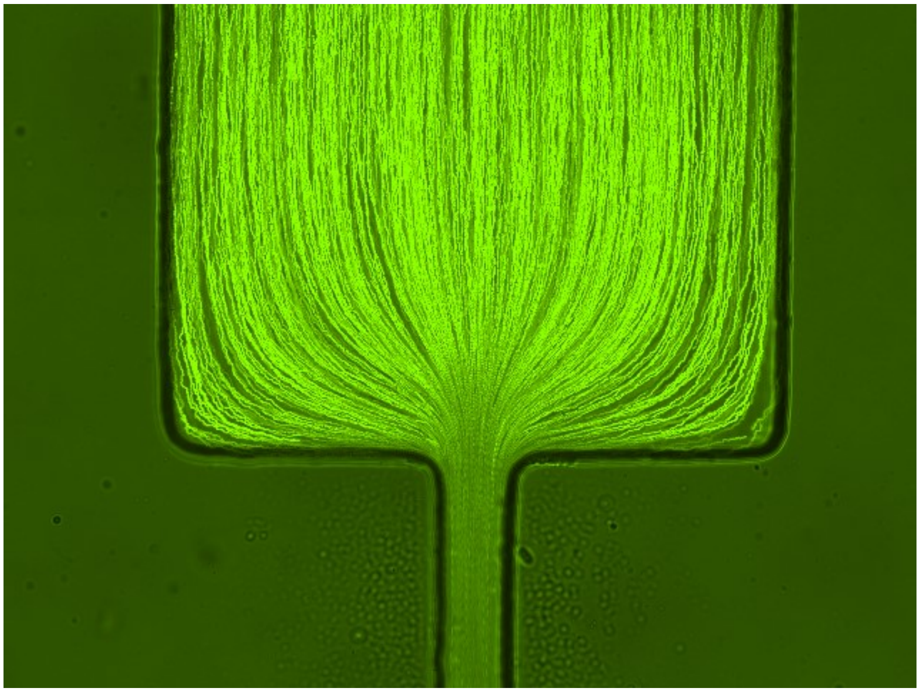

Figure 9 Solution contained 5mM buffer, AC set at 200V, DC set to 10V

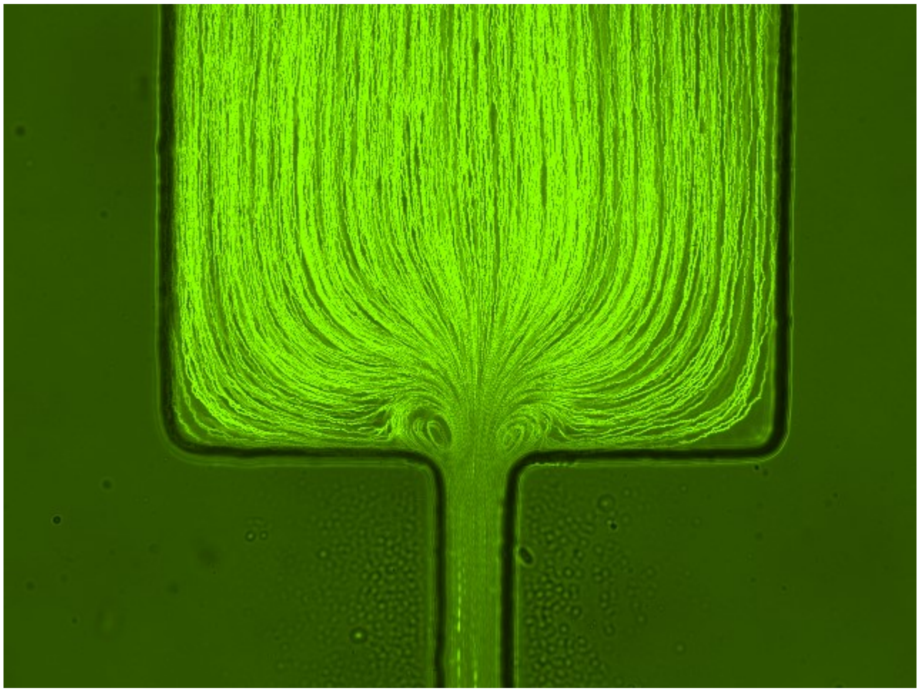

Figure 10 AC increased to 250V

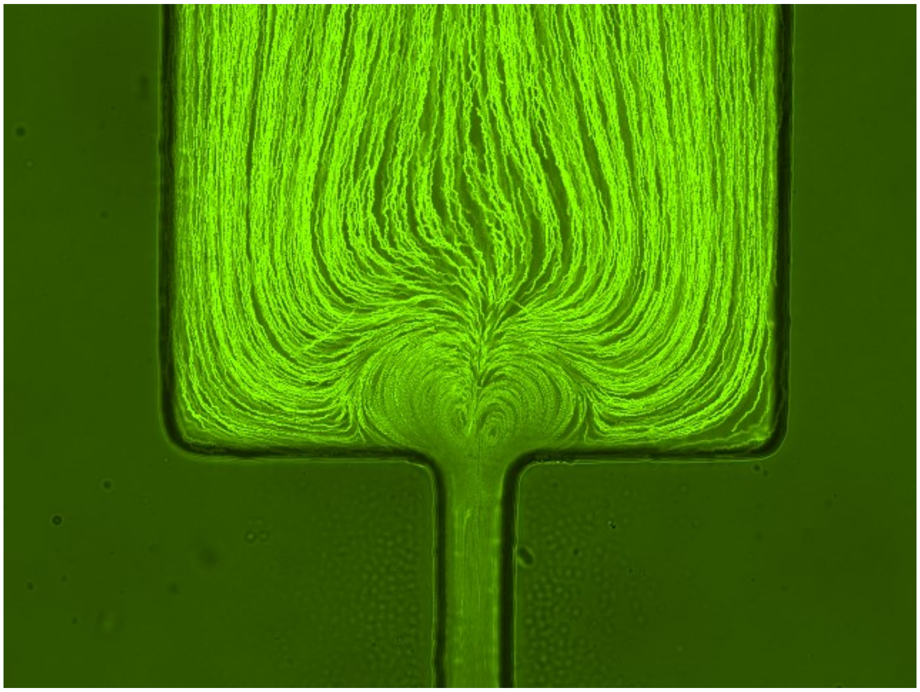

Figure 11 AC increased to 300V

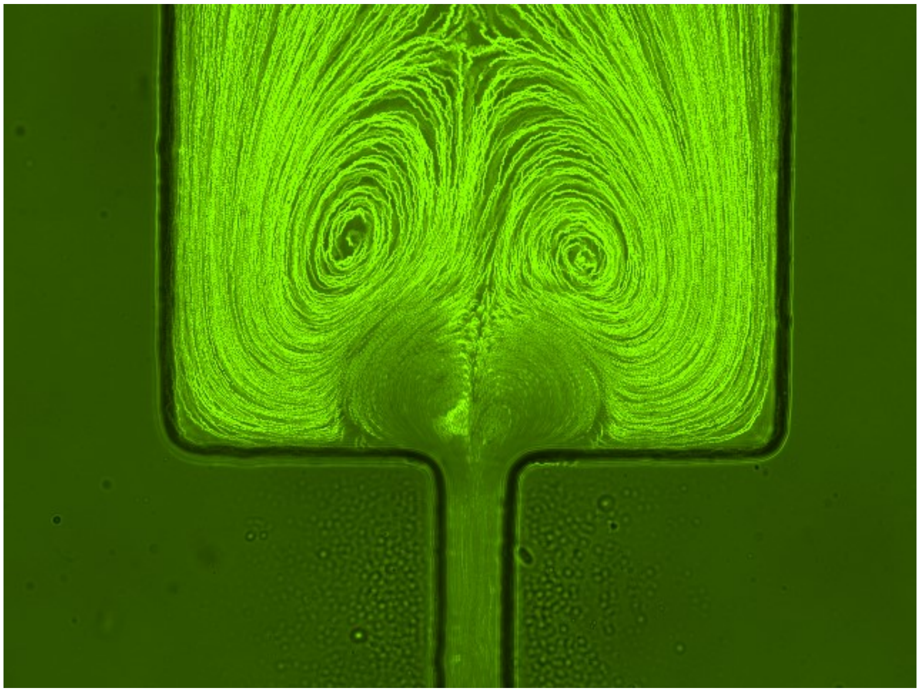

Figure 12 AC increased to 400V

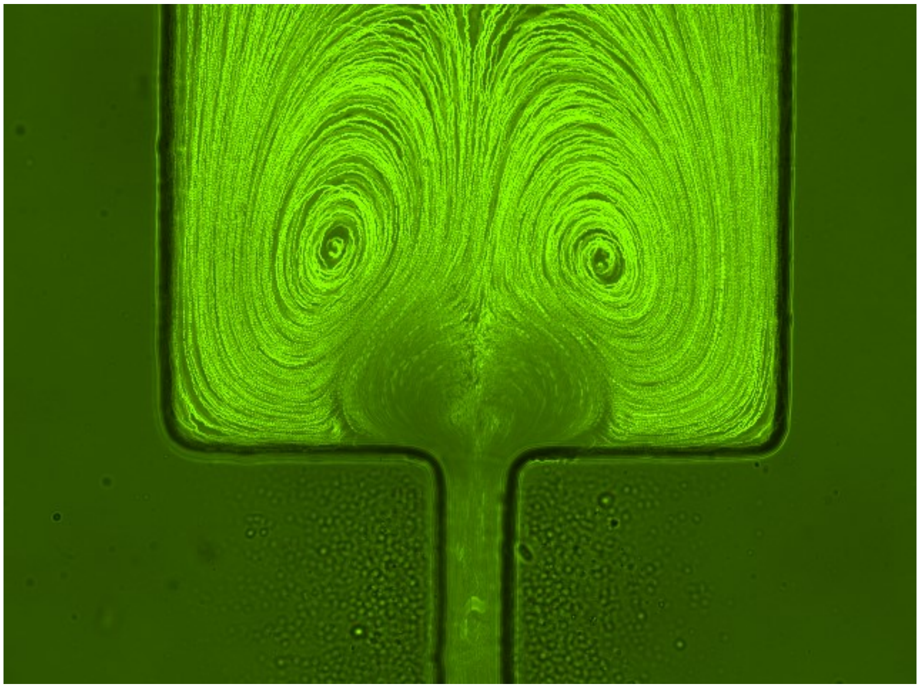

Figure 13 AC increased to 450V

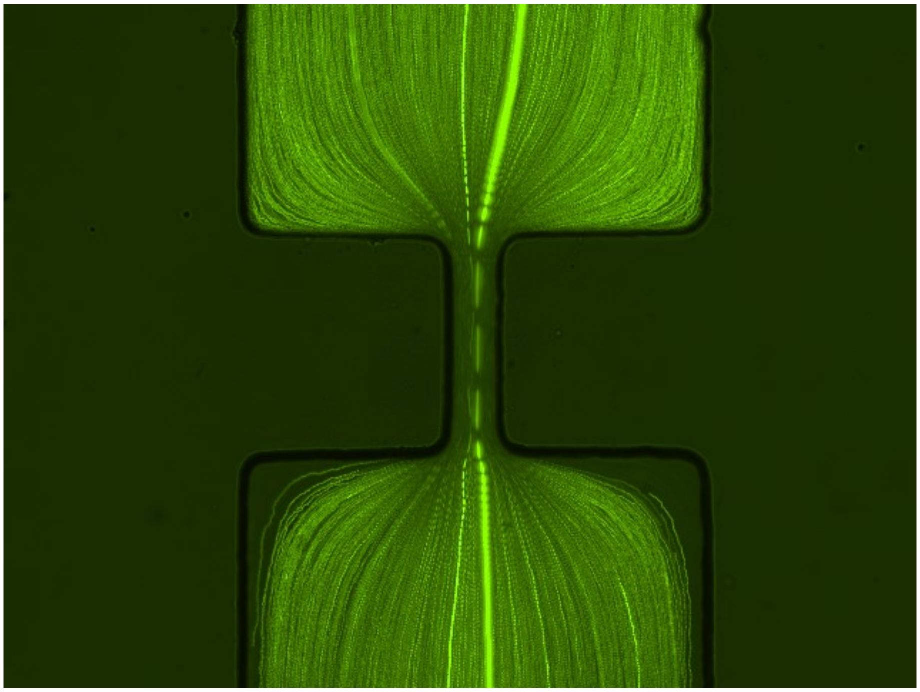

Figure 14 Solution contained 0.1mM buffer and 1000ppm PEO, AC set to 300V, DC set to 10V

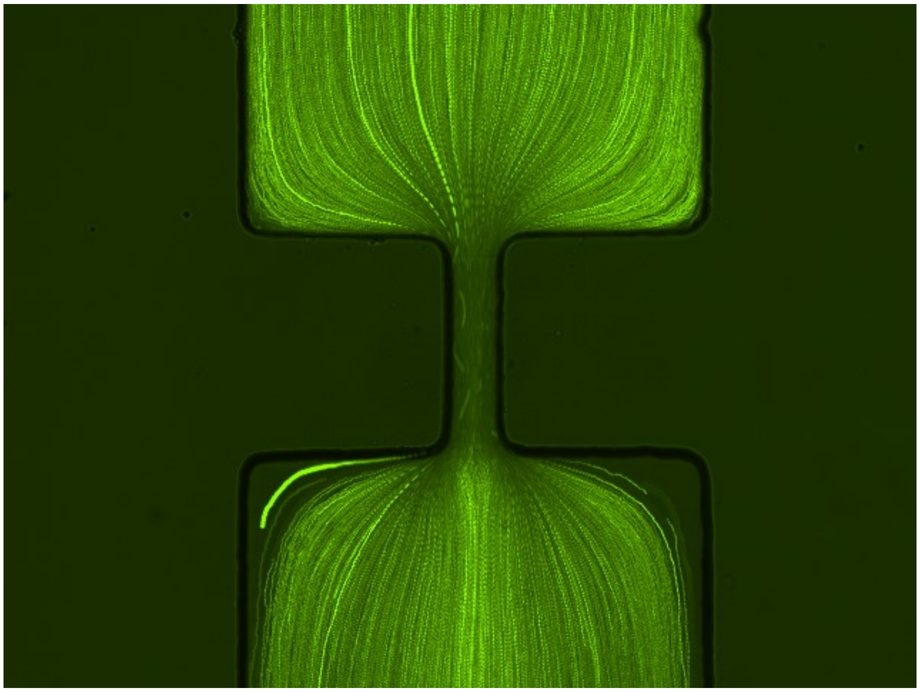

Figure 15 AC increased to 400V

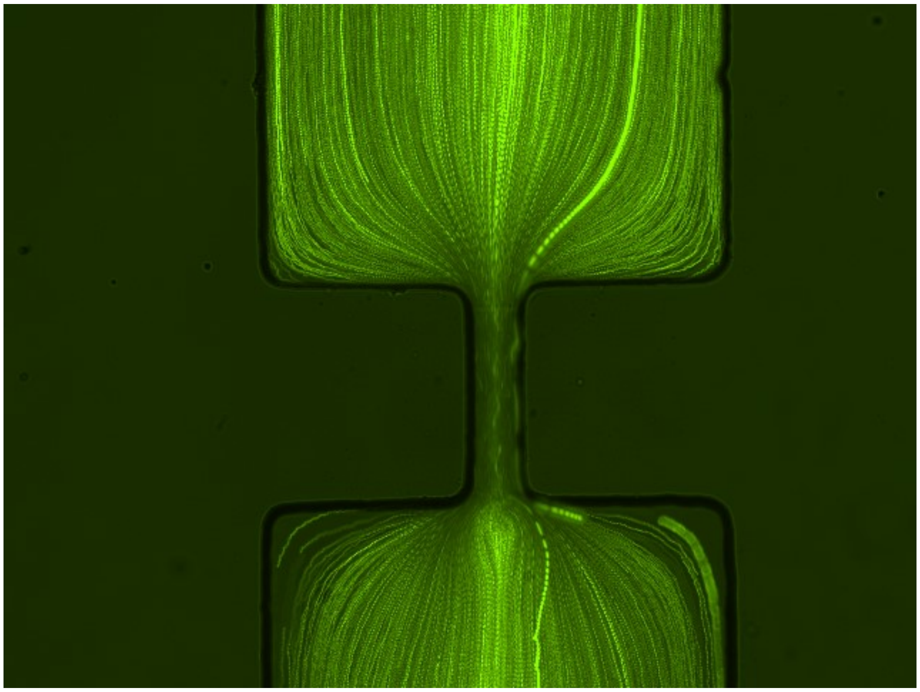

Figure 16 AC increased to 450V

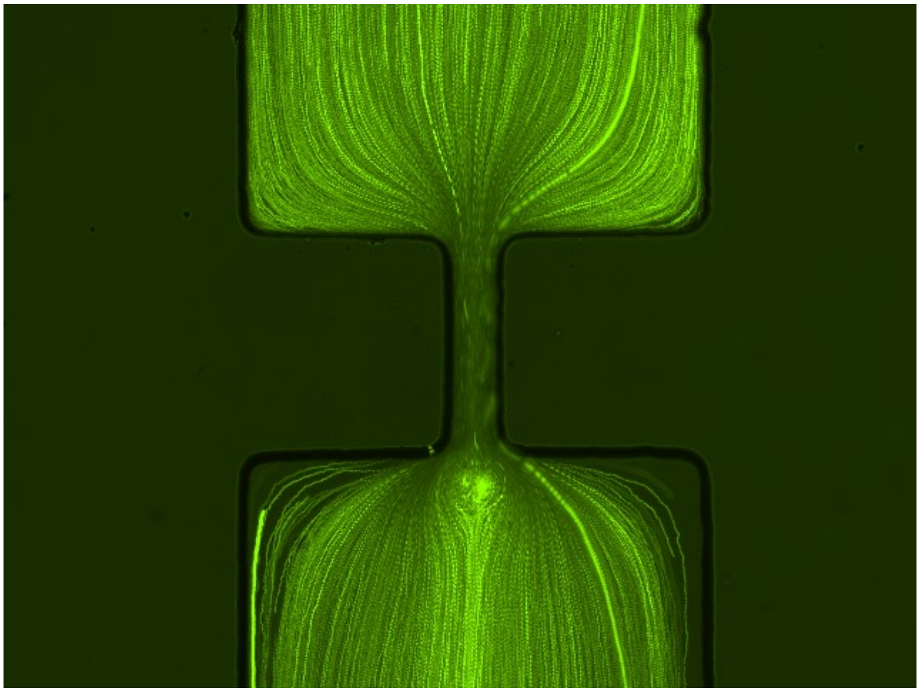

Figure 17 AC increased to 500V

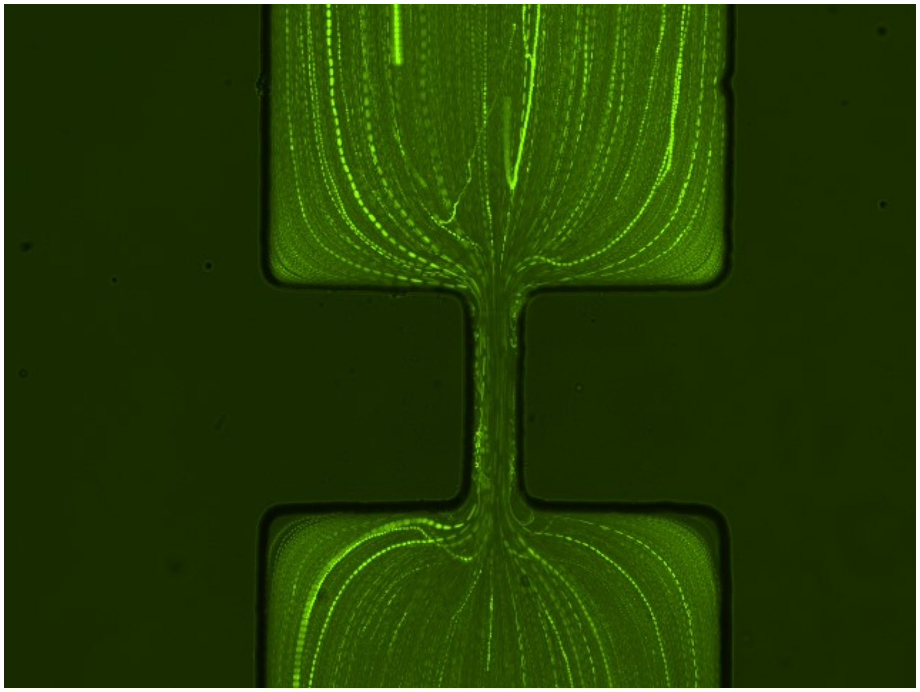

Figure 18 AC set to 0V, DC increased to 100V

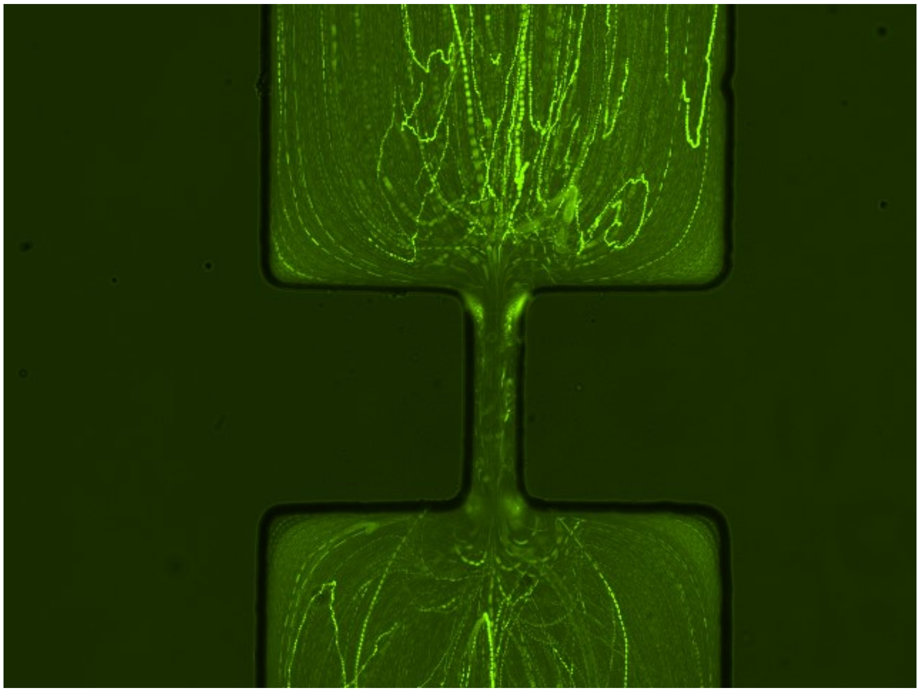

Figure 19 DC increased to 200V

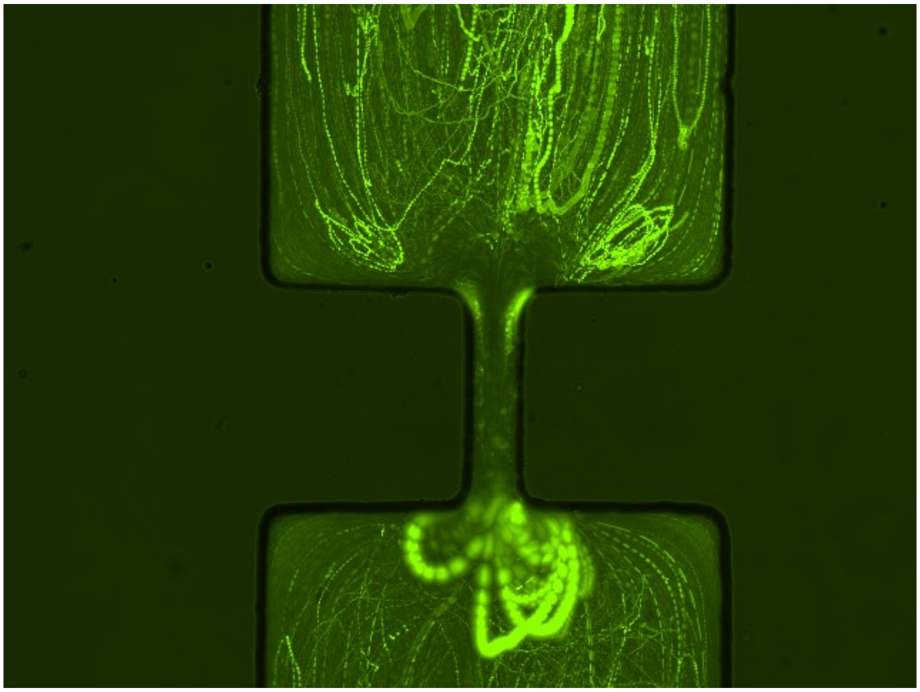

Figure 20 DC increased to 300V

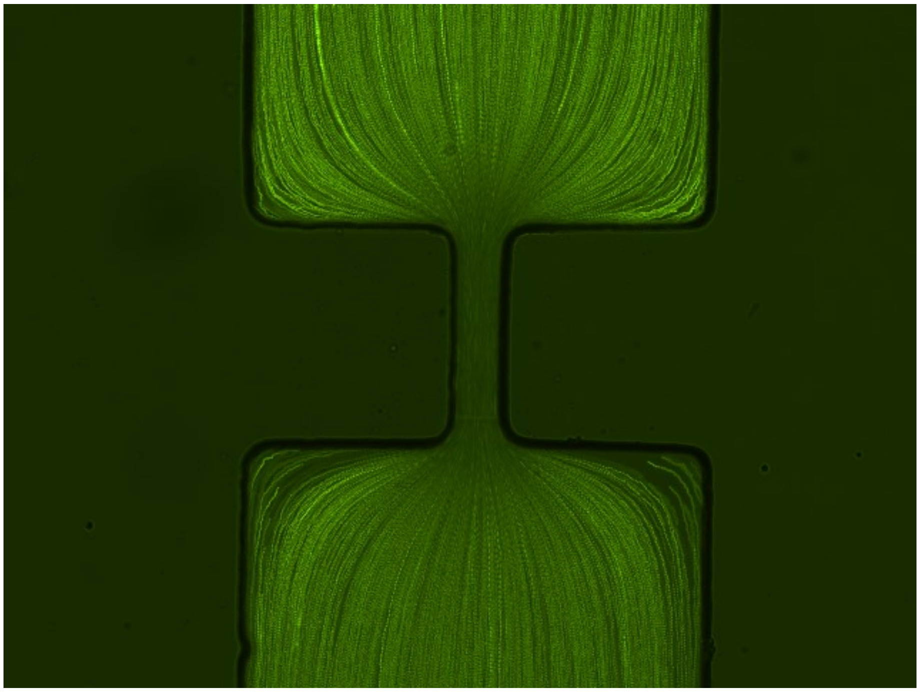

Figure 21 Solution contained 1mM buffer and 1000ppm PEO, AC set at 200V, DC set at 10V

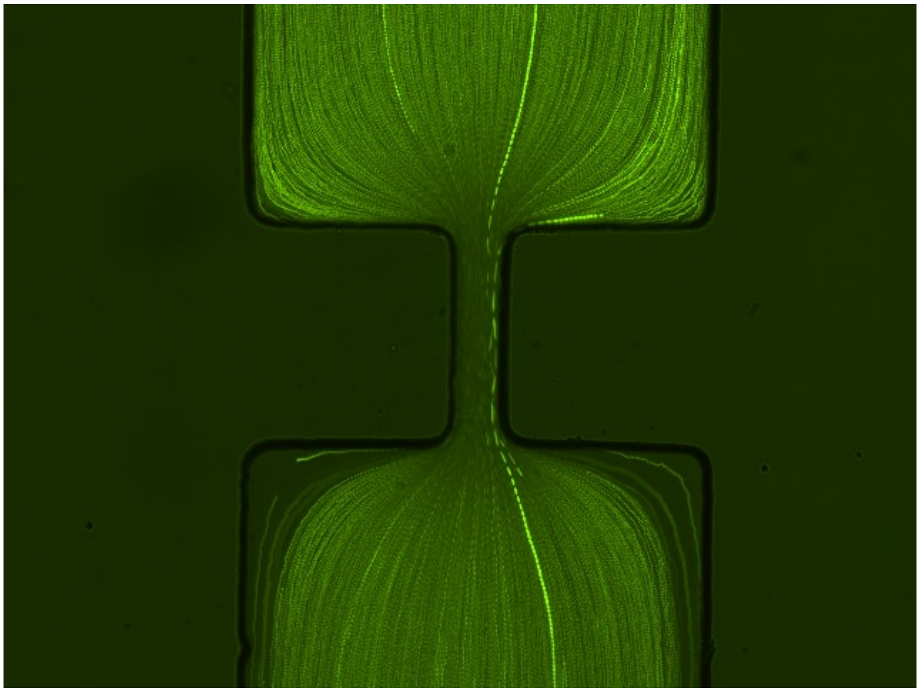

Figure 22 AC increased to 300V

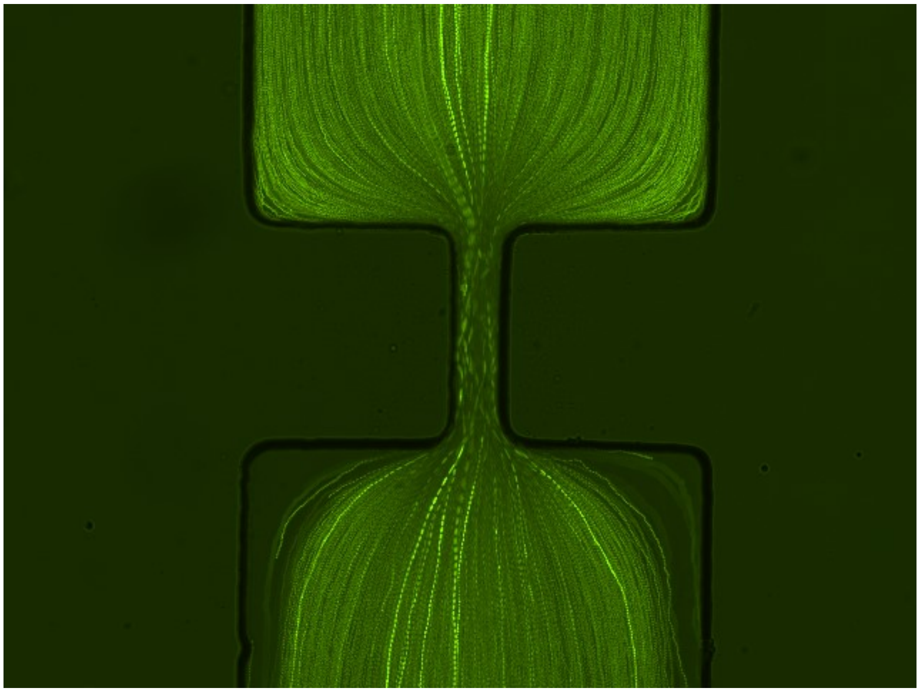

Figure 23 AC increased to 400V

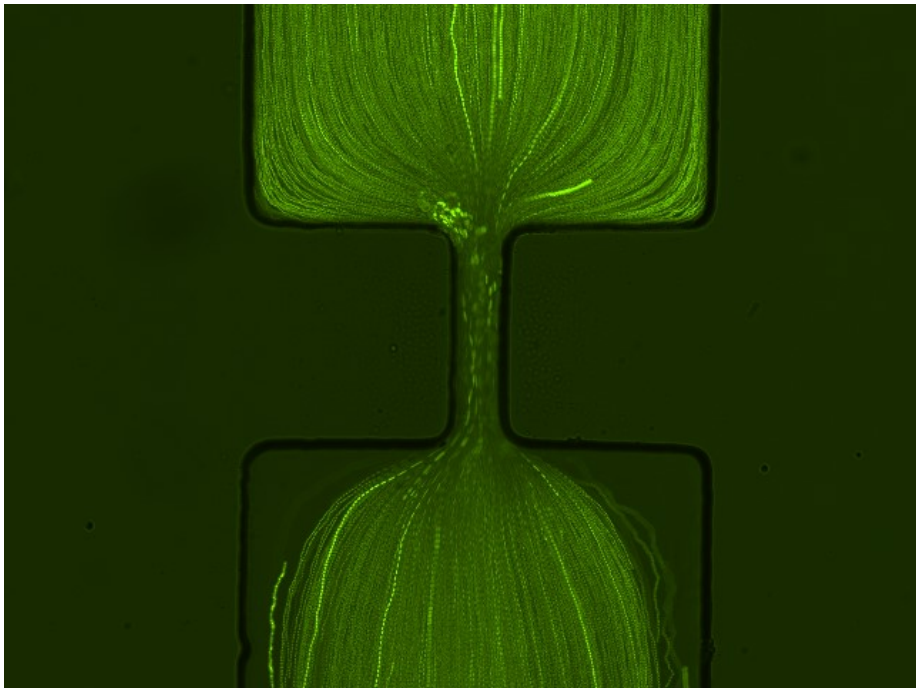

Figure 24 AC increased to 450V

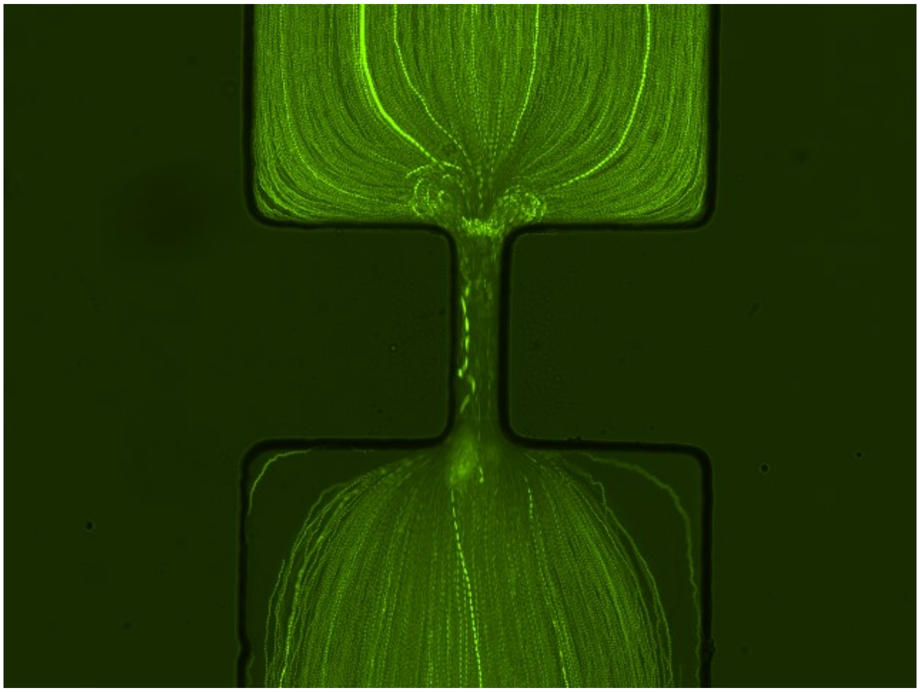

Figure 25 AC increased to 500V

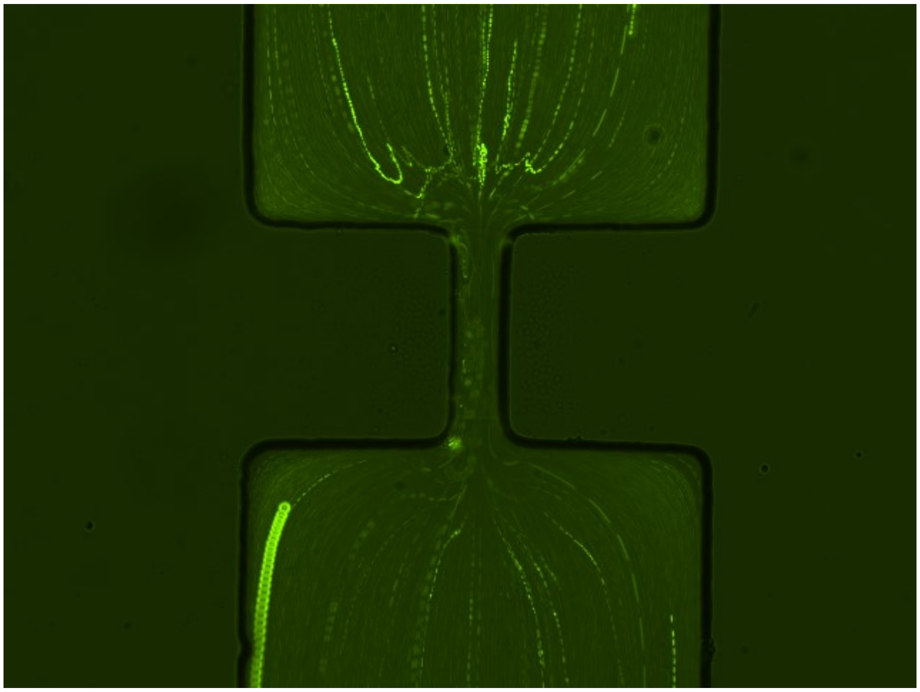

Figure 26 AC set to 0V, DC increased to 200V

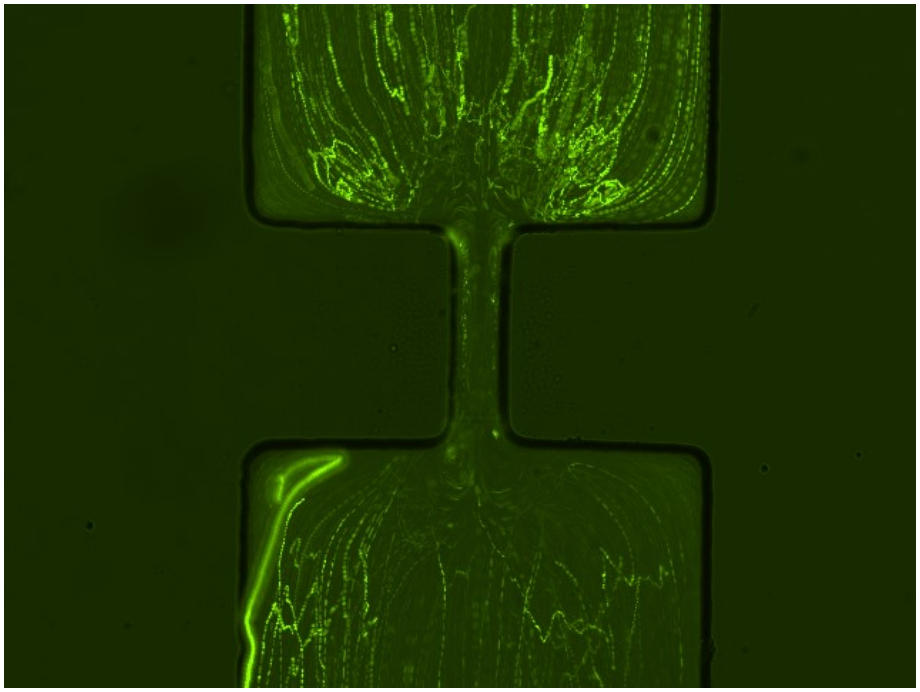

Figure 27 DC increased to 300V

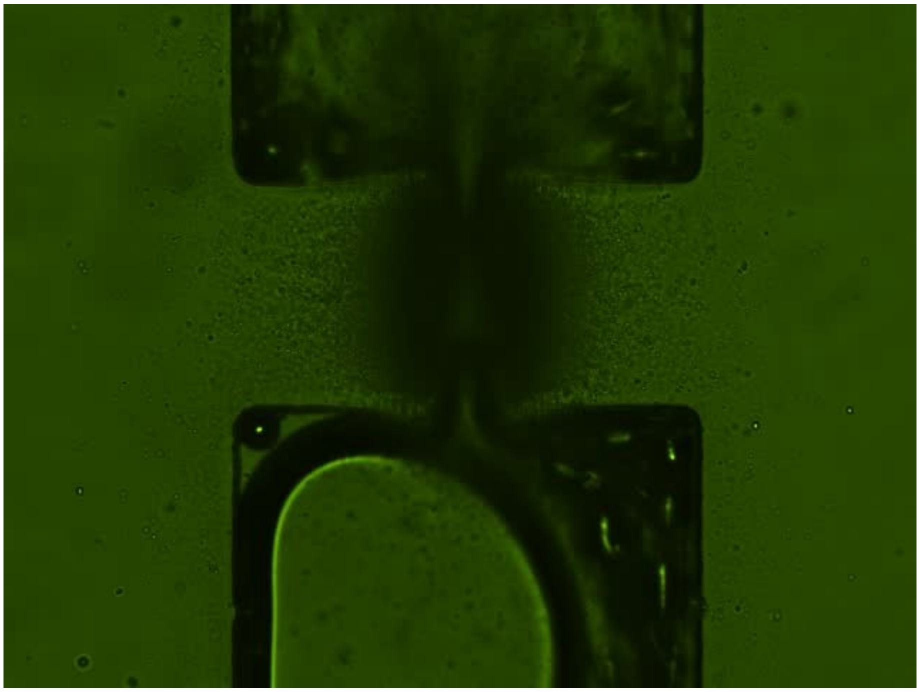

Figure 28 A burned microchannel