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Clogging of Colloidal Particles in a Microchannel using an Electro-Osmotic Micropump

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Abstract

When a mixture of colloidal particles and a high salt concentration flow through a microchannel at one side via an electro-osmotic micropump, and a low salt concentration flows into the channel from the other side. A clog of particles might grow inside the channel at the low salt side. I try to determine how far such a clog grows into the channel for different salt concentrations and potentials. Using Python, I will also determine the flow velocity of the particles and electrical current through the channel. Under the conditions I probe, I did not observe clogging systematically but laid a good foundation for further research on this topic.

Contents

1 Introduction

The presence of colloidal particles (CPs) in so-called micro-channels is an extremely complex system with a large range of applications in filtration, separation and lab-on-chip devices. These applications are used in a big diversity of industries, from the medical world to chip factories.

There are two common used methods to flow fluid through these micro-channels. One is via a pressure-driven flow, which is inconvenient because the average flow velocity decreases with the square of the channel diameter. The other option is also the method of choice; electro-osmotic pumping (EOPing). A challenge of using an EOP is that the micro-channel can become clogged with CPs.

Zhu et al. studied the transport of CPs through a straight silica microchannel by EOPing and its potential clogging. Imposing an (time dependent) electrical field and a salt gradient gave them the possibility to (using video microscopy) study the effect of the CPs. They did observe CP aggeragtion at one end of the channel. This was with an electrical field which was in the opposite direction to the salt concentration. Which eventually lead to a growing clog at the end of the channel. They did find a way to prevent this clogging of the channel. By inverting the applied potential for a short time, the aggregated CPs dispersed and the channel was free once again, as can be seen in Figure 1. They used a square wave potential to clear the channels. For this project *Zhu et al.* also performed simulations which showed that a clog will rise at the end of the channel and grow inside of the channel. This was the subject that *Zhu et al.* [6] were studying and this study is an follow-up study of the simulations of *Zhu et al.*.

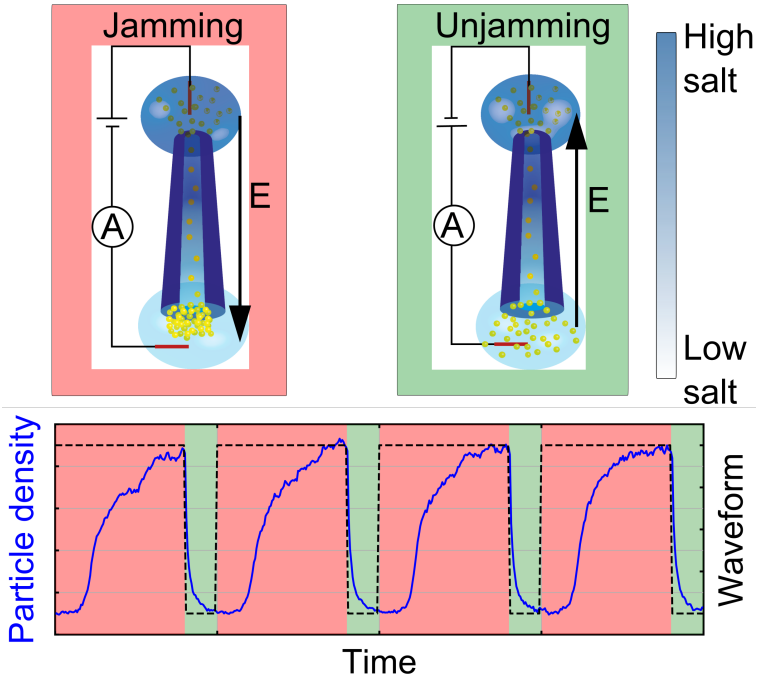


Figure 1: A schematic view of the clogging and declogging of the channel due to the change in potential direction [6]

I have done the experimental work to see whether these simulations are right. I studied the transport of CPs through a PDMS[1] channel via EOP using a DC wave so that the clog inside of the channel grows. How far this clog grows inside of the channel depends on the used potential and salt gradient, according to the simulations. Using the same video microscopy as *Zhu et al.* I can roughly see how far this clog grows inside of the channel but using Python I can qualitatively say how far the clog grows inside of the channel. During this clogging, salt ions will flow through this channel, implying a current. So I will also measure the current through the channels for every potential and salt concentration. Using Trackpy, I will also measure the velocity of the particles which are flowing through the channels.

2 Theory

2.1 Electrical double layer

When a material is exposed to a material with mobile ions, a structure of charges, know as the electric double layer (EDL), forms around the interface of the two materials[2]. The first layer, the surface charge (either positive or negative), consists of ions adsorbed onto the object due to chemical interactions. The second layer is composed of ions attracted to the surface charge via the Coulomb force, electrically screening the first layer. When the PDMS is exposed to electrolyte, the electric double layer is formed at the interface of electrolyte and PDMS. The PDMS channel gets a negative charged surface, this attracts positive ions which form the first layer (stern layer) on the surface of the PDMS, balancing the negative charge on the surface. The first layer of positive ions then electrically attract negative ions which will form a second layer of ions, known as the diffuse layer. Because the surface of the PDMS consist out of negative charges, the net charge of the EDL will be positive, balancing the surface charge. Because these layers 'stack' on top of each other with a certain distance between the layers, the potential will decrease as distance from the surface increases as can be seen in Figure 2.

2.2 Electro-osmosis

Before introducing the electro-osmosis, we should first introduce the important slipping-plane shown in Figure 2, which is the separation between the first layer (Stern) and second layer (Diffuse layer). Below the slipping plane, the charges are fixed, outside the plane charge can experience tangential motion relative to the charged surface. The electric potential on this plane is called the Zeta potential (ζ potential). The ions outside of the slipping plane can be moved by an external filed *e.g.* a pressure field and/or an electric field. If the charged wall is exposed to a external electric filed, which will exert a strong electromotive force on the mobile ions present inside the diffuse layer. This electromotive force drags the ionic liquid in the direction of the applied field, resulting in the actuation of the electro-osmotic flow (EOF) shown in Figure 3[3]. The velocity approaches zero at the slip plane, and the electro-osmotic velocity is the velocity of the electro-osmotic flow in the liquid beyond the EDL[4]. The velocity of electro-osmotic flow can be describe by:

[1] A schematic view of such a PDMS channel can be seen in Figure 6

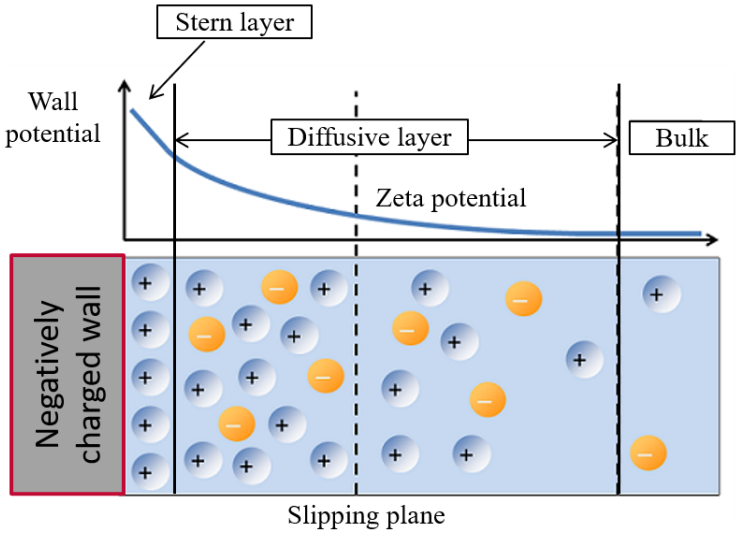


Figure 2: A schematic view of the electrical double layer and the corresponding electrical potential [1].

$$u_{eo} = \mu_{eo}\vec{E} \tag{1}$$

$$\mu_{eo} = \frac{\epsilon_0 \epsilon_r \zeta_{wall}}{\eta}, \tag{2}$$

Where $\vec{E}$ is the electric field, μ_{eo} is the electro-osmotic mobility, ϵ_0 is the permittivity of a vacuum, ζ_{wall} is the Zeta-potential of the channel wall, ϵ_r is the dielectric constant of the electrolyte solution, and η is the solution viscosity.

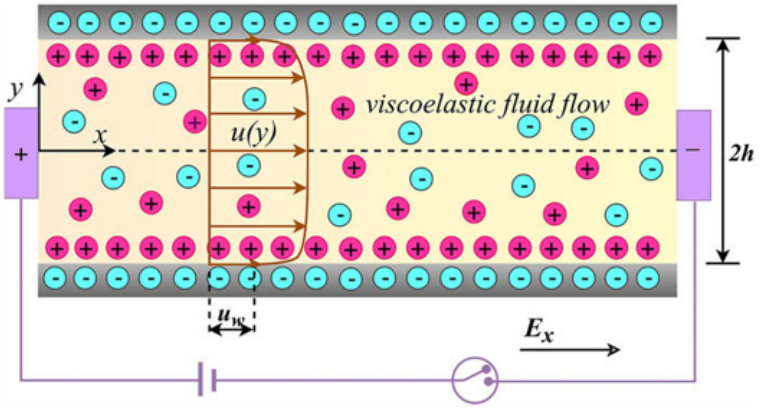


Figure 3: Schematic representation of a purely electro-osmotic flow of the viscoelastic fluid in a parallel plate microchannel. The plates are separated by a distance 2h, while coordinate axes are placed at the left end of the channel center. The externally applied electric field Ex set up by placing two electrodes at both ends of the channel drives the flow in the positive x direction.

2.3 Electrophoresis

Electrophresis is the movement of the charged colloidal particles immersed in a liquid, under the influence of an electric field as shown in Figure 4. The forces that play a role in this phenomenon are [4]:

1. **The driving electrostatic force**, which is the coulomb force of the electric field acting on the surface charge;
2. **The frictional force**, the resistance due to the viscousity of the fluid;
3. **The electrophoretic retardation force**, this force is caused by the moving countercharge from the EDL. It depends on the composition of the EDL and the ionic mobility;
4. **The relaxation force**, this is by reason of non-coinciding charge-centers. A small dipole moment may be induced due to a shift in the EDL.

The rigorous solution for the electrophoretic mobility with 4 mentioned forces require the formulation of hydrodynamic equations, coupling them to the electric field equations and solving them with proper boundary conditions. For simplification, we can use a relatively simple laws that are valid under limiting conditions and recur in a variety of practical situations. So we can use the electrophretic velocity of a colloidal particle $u_{CP_{ep}}$ which is simply proportional to the applied field:

$$\vec{u}_{CP_{ep}} = \mu_{CP_{ep}} \vec{E} \tag{3}$$

$$\mu_{CP_{ep}} = \frac{\epsilon_0 \epsilon_r \zeta_{CP}}{\eta}, \tag{4}$$

Where $\vec{E}$ is the electric field, $\mu_{CP_{ep}}$ is the electrophoretic mobility, ϵ_0 is the permittivity of a vacuum, ζ_{CP} is the Zeta-potential of the colloidal particle, ϵ_r is the dielectric constant of the electrolyte solution, and η is the solution viscosity.
However, all the forces and velocities that are described in the previous sections don't take the presence of a salt gradient into account. It will induce two new phenomena:

1. **Diffusio-osmotic flow**, which will alter the velocity of the electro-osmotic flow;
2. **Diffusio-phoretic flow**, which will alter the velocity of the electrophoretic flow;

Both flows will alter the velocity of the CP and will be discussed in the following sections.

2.4 Diffusio-osmotic flow

As said before, due to the presence of a salt gradient, the electro-osmotic velocity will be altered. The new velocity of the electro-osmotic and the diffusio-osmotic flow is:

$$\vec{u}_{do} = \vec{u}_{eo} - \mu_{do} \vec{E} \log(c_+ + c_-) \tag{5}$$

$$\mu_{do} = \frac{\epsilon_0 \epsilon_r}{\eta} \left(\beta \frac{k_B T}{e} \zeta_{wall} + \frac{\zeta_{wall}^2}{8} \right) \tag{6}$$

$$\beta = \frac{D_+ - D_-}{D_+ + D_-} \tag{7}$$

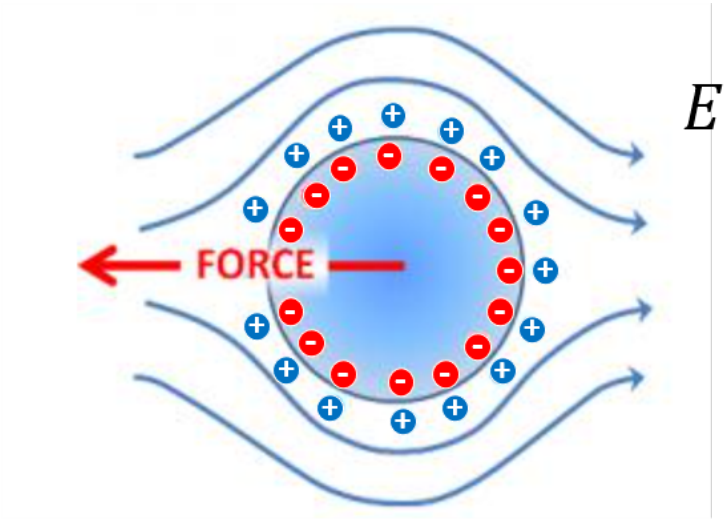


Figure 4: Schematic representation of electrophretic force on a colloidal particle.

Where μ_{do} is the diffusio-osmotic mobility [6]. The factor β is the reduced ion-diffusivity difference and indicates that there is an osmotic contribution from ions having different electric mobilities. The $c_{\pm}$ factors indicate the respectively sodium/chlorine concentrations. Where $D_{\pm}$ represents the the sodium/chlorine diffusion constants. Finally, the pore walls are impenetrable to the ions.

2.5 Diffusio-phoretic flow

The other flow that is altered is the electrophoretic flow. The complete velocity of the electrophoretic and diffusio-phoretic flow is [8, 9]:

$$\vec{u}_{CP_{dp}} = \vec{u}_{CP_{ep}} - \mu_{CP_{dp}}\vec{E}\log(c_+ + c_-) \tag{8}$$

$$\mu_{CP_{dp}} = \frac{\epsilon_0\epsilon_r}{\eta}\left(\beta\frac{k_B T}{e}\zeta_{CP_{ep}} + \frac{\zeta^2_{CP_{ep}}}{8}\right) \tag{9}$$

With $u_{CP_{ep}}$ is the electrophoretic velocity of the CP, so identical to eq.(3). Where eq.(9) is the diffusio-phoretic mobility. Where $\zeta_{CP_{ep}}$ is the NP zeta potential [7].
With the induced salt gradient, the eventual velocity of the CP's will be the sum of eq.(5) and eq.(8). The only remark is that the sign of the phoretic terms should be negative, this is because the particles are free to move. So the final equation for the veloctiy of the CP's is:

$$\begin{aligned}\vec{v} &= \vec{u}_{do} - \vec{u}_{CP_{dp}} \\ &= \mu_{eo}\vec{E} - \mu_{do}\vec{E}\log(c_+ + c_-) \\ &- \mu_{CP_{ep}}\vec{E} + \mu_{CP_{dp}}\vec{E}\log(c_+ + c_-)\end{aligned} \tag{10}$$

2.6 Ohm's law

As said before in Section 1, I measure the electric current through the channels. I use Ohm's law for this. Electric current is the movement of electric charge such as subatomic charged particles or ions. Ohm's law relates the current I (A) to a voltage V (V)and a resistance R (Ω) via Equation (11)

$$I = \frac{V}{R} \tag{11}$$

3 Setup

A schematic sketch of my setup can be seen in Figure 5, while all the devices that I used are shown in Table 1. The devices of Table 1 that are not shown in Figure 5 will be discussed in the upcomming sections.

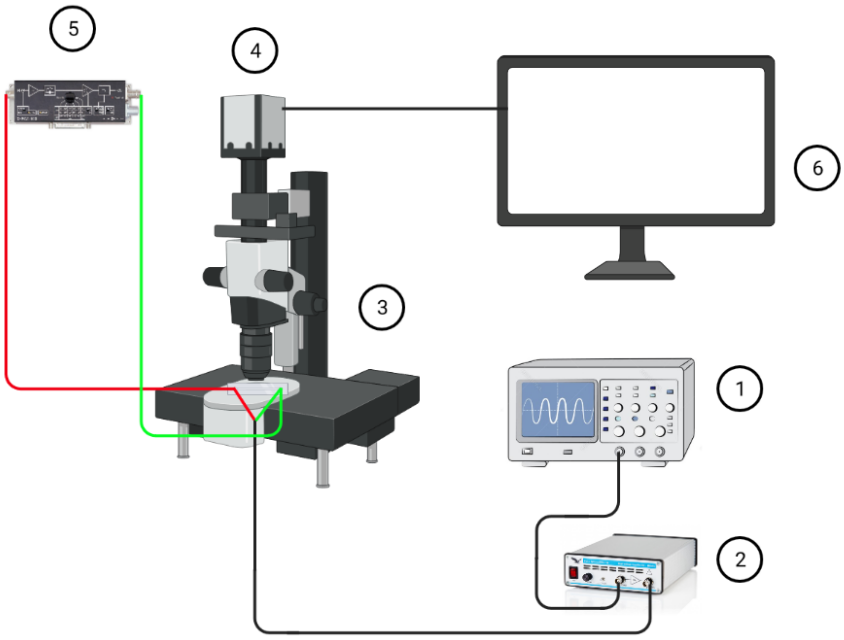


Figure 5: A schematic sketch of my setup. The black lines indicate power cables, while the green line indicates the +pole and the red line indicates the -pole of the electric field. with (1) the oscilloscope, which will generate the electric field. (2) is the voltage amplifier, which will amplify the electrical field generated by the oscilloscope. (3) is the microscope with a sample on it, the red and green line are connected to the sample. (4) is the camera which will record the sample. The video of this sample is displayed on the computer (6). While the (5) represents the current amplifier which I use to measure the current through the channels. This image, Figure 6 and Figure 7 are created using the program BioRender.

Device	Model
Microscope	Axiovert 135
Oscilloscope	Keysight InfiVision DSOX
Current amplifier	Femto DSPCA-200
Voltage amplifier	Falco systems WMA-100
Nitrogen gun	Nitro-4T-FT
Corona discharger	BD-20A high frequency generator

Table 1: Table of all the devices that I used for my experiment, including the name of the models.

4 Method

4.1 Acquiring a PDMS channel

To get a mixture which, when dried, contains the PDMS channels. I need to mix silicone elastomer and silicone elastomer curing agent with a ratio 10:1. There will be air bubbles in this mixture which will be harmful for the channels. To remove these bubbles, I placed the mixture in a transparent degas chamber which will be vacuumed by a vacuum pump , this will take ±20 minutes.

After this, the PDMS mixture can be poured on the so-called SU-8 mode which contains the patterns of the channels. By pouring the PDMS on this wafer, the channels are formed between the interface of the SU-8 module and the PDMS. During this pouring, bubbles are once again formed in the PMDS mixture. These bubbles are again removed by placing the SU-8 module, with the liquid PDMS on it, in the degas camber and vacuum this box until all bubbles are gone.

The PDMS still is in a liquid state so it needs to be dried. This is done by placing it in a oven or on a hotplate for minimally two hours at 68 $C°$. Two hours should be enough but it can also be done overnight to ensure that the PDMS is fully hardened. After this, the PDMS is covered with tape on both sides to prevent getting dust on the channels.

4.2 Assembling a PDMS sample

To assemble a sample, start with a piece of PDMS containing the channels as can be seen in Figure 6. Cut through the big reservoirs such that the channel is connected to air. So from A to B and from C to D in Figure 6. After this is done, clean a cover glass. This is done by first spraying the cover glass with isopropanol, than ethanol and lastly DI water. Repeat this procedure three times, then dry the cover glass with the nitrogen gun.

Now I can treat the cover glass and PDMS with the corona discharger[5]. First I need to peel the tape of the PDMS from the side which has the channels on the upper half[2]. This side will

[2]The side containing the channels can be recognized by the following. There are some numbers and letters on the

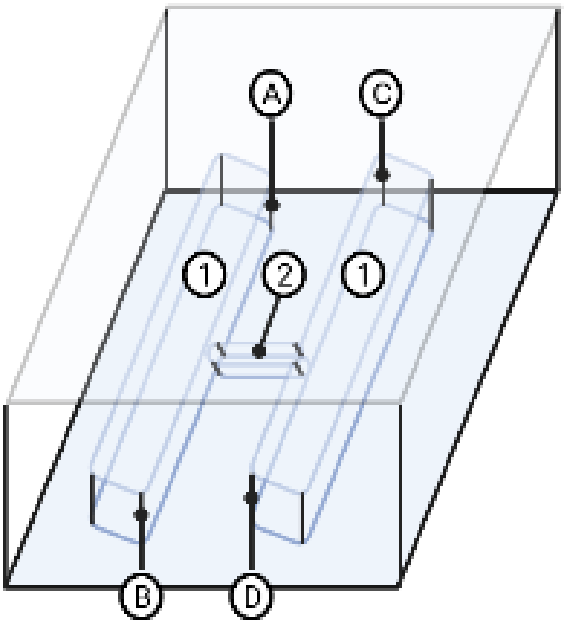


Figure 6: A schematic view of a piece of PDMS containing two big resevoirs (1) (which will be cut off) and a single channel (2). This is a simplified image. In reality, there will be four channels. The dimensions of the used channels can be found in Section 5.1.

be attached to the cover glass. I treat the cover glass and the PDMS with the corona discharger for about 3 minutes by hovering over the PDMS and glass with the corona dicharger. By doing this, the Si-OH groups in both the PDMS and the glass are activated. These groups will bound to each other and work as glue between the PDMS and the glass. After this is done, I can stick the treated sides of the PDMS and the cover glass together and wait for 30 seconds. While waiting I also press the PDMS and glass against each other so that they will stick even better.

4.3 Making and filling a reservoir

When the PDMS is connected to the glass, I can make a reservoir. By making a wall with glue[3]. By encircling the channels, a (external) reservoir is formed. I than screw a press on top of the sample to keep the PDMS from detaching from the glass. This press has holes in it on the same place as were the swimming pools are so that the liquid can eventually flow into the channel. A schematic image of a sample including the swimming pools and press can be seen in Figure 7. I insert the liquid in the swimming pool by hand using a pipet.

PDMS, these give the dimensions of the channels. For the upper side, these letters and numbers are not mirrored.

[3]I use the 'Griffon Combi Snel Lijm'

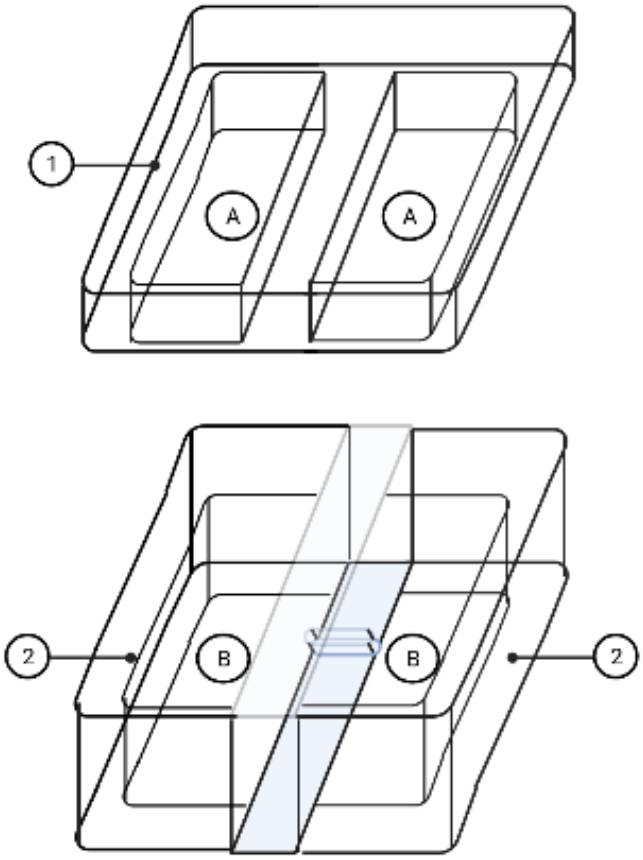


Figure 7: A schematic view of a piece of PDMS including the press (1) that can be screwed on top of the sample. The swimming pool (2) is made out of glue to keep the liquid from flowing away from the channel. When the press is screwed on top of the sample, I can inject the liquid via the hole in the press (A) in the swimming pool (B)

4.4 Applying the potential

To apply the potential to the channels, I tape the plus pole to the side of the channel which will be filled with the high salt concentration. In the same way, the minus pole is connected to the channel side containing the low salt concentration.

These two poles are connected to a power amplifier which is connected to the oscilloscope. By doing this I'm able to apply potential up to 50V to the channel via a DC or square wave current. Important is that the side of the channel which contains the high salt concentration, is connected to the positive pool of the oscilloscope. Otherwise, no clogging will occur.

4.5 Acquiring a measurement

To start a measurement, it is important to inject the low salt concentration (DI water) first. By doing this, all the air inside the channels will be able to escape. When the air has escaped (which will be visible with the microscope), the mixture of the particles and high salt concentration can be injected. When the pressure between both sides is balanced (so the particles remain stationary inside the channel), the potential can be applied and the measurement can start.

As said before, I want to determine how far a clog of particles grows into a channel. So when the flow has reached an equilibrium, I can begin applying the potential (a DC current). When the potential is applied particles start to aggregate at the low salt concentration side of the channel. The aggregated particles form a clog and this clog grows into the channel.
Adding a current amplifier to the circuit enables me to measure the current through the channel. The resistance through the channels can be altered using this current amplifier.The oscilloscope enables me to measure the voltage on the channel. This gives me, using Equation (11), the current that flows through the channel.

The camera that I use has an image-saving function. Enabling this function for 3 seconds at the maximum frame rate gives me an image sequence. This sequence is converted into a tiff-file using the computer-program ImageJ. By importing this tiff-file into python, enables me to use Trackpy to track (and calculate the flow velocity of) the particles which are shown in the video. An example of how this tracking looks can be seen in Section 5.4. After the measurement is done, I place the sample in a Supersonic bath filled with DI water. The supersonic bath removes all the particles and cleans the sample so that I can use it again for a new measurement. After it is cleaned in the supersonic bath, I dry it using tissues and the nitrogen gun until the sample is completely dry. I reuse a sample twice before I replace it by a new one.

5 Results

5.1 Dimensions

There is a large variety of channel dimensions. The length and width of the channels can vary, while their height is constant. Their length can be $\frac{1}{2}$, 1 or 2 mm. While the width of the channels can be 10, 20 or 50μm. The height of the channels is 20 μm.

I have chosen to use channels which are 2 mm long. This is because $\frac{1}{2}$ mm long channels are practically to small to handle. For example, when placing the PDMS in front of the corona discharger the PDMS will easily tip over and attract dust. If this happens, the PDMS will be too dirty to stick to the glass. Another downside is that the dust can block the channels and the sample will be useless. The same goes for the 1 mm channels.

As said before, there are three possible widths of the channels. I have chosen to use the channels which are 20μm wide. This is because I think that the channels which are 10μm are to small to properly see them with the microscope. The channels with a width of 50μm are also not suitable. They are not suitable because the high and low salt concentration will mix up to quickly. So the

salt gradient will not be steep enough for the diffusiophoretic and diffusio-osmotic flow to be at play. If this is the case, no clogging will occur.

5.2 Used parameters

The two parameters which will vary are the voltage (V) and the salt concentration ($mMol$) of the high concentration side. As said before, this research is a follow up study of *Zhu et al.* [6]. However, I will use different voltages and salt concentrations than *Zhu et al.* did[4]. *Zhu et al.* used multiple salt concentrations in the range from 0.5mM - 10mM and potentials in the range of -100V to +100V. I will perform measurements with an applied potential ranging from 1 to 50 Volts. The possible potentials can increase linearly, however the salt concentrations should increase logarithmically. So I will use salt concentrations of 2, 4 and 8 mM NaCl.

5.3 Calibration

It is important to add a scale of distance to the images I take with the microscope, which I will determine via a calibration. For this calibration, I use a small ruler which I place under the microscope as can be seen in Figure 8. Using the computer program ImageJ, I counted the pixels between the outer, larger, lines. By doing this I get the physical distance per pixel (DPP) and with that I can determine how far a clog has grown inside a channel. I repeated this procedure for four magnifications: 2.5x, 5x, 10x, 20x and the corresponding distance per pixel can be seen in Table 2.

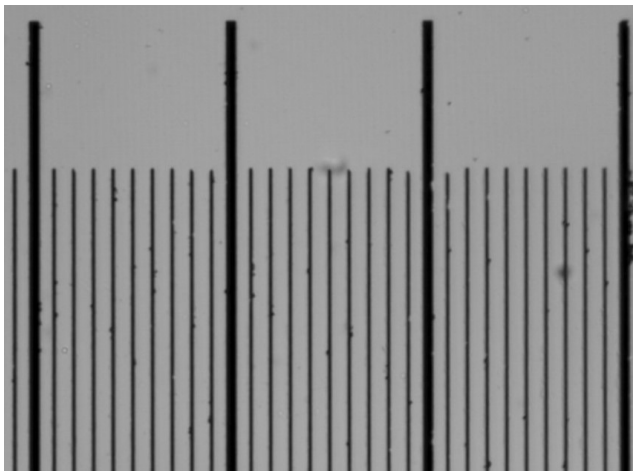


Figure 8: Image of the calibration sample. I used a magnification of 20x. The distance between the two outer, larger, black lines is 0.3 mm.

[4]The reason for this is that the tube that *Zhu et al.* used are much longer than the channels that I use (10 mm vs 2 mm)[6]. Therefore, I can use much smaller potentials and lower salt concentrations.

Magnification	DPP (μm)
20x	0.377
10x	0.763
5x	1.531
2.5x	2.985

Table 2: DPP for the different magnifications of the used microscope.

5.4 Data processing

5.4.1 Clogging of the channel

After ±20 minutes clogging starts to become visible at the low salt side. This clog will start to grow inside the channel until a certain spatial point. For every used salt concentration and applied potential this point is somewhere else. To determine this point, I take the following steps.

First I make a snapshot of the end of the channel. An example of this can be seen in Figure 9.

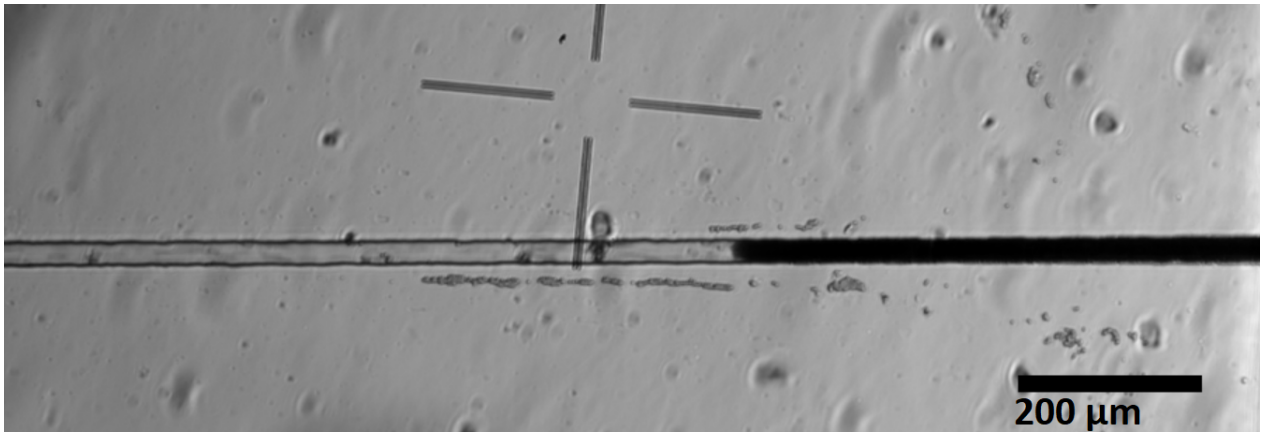


Figure 9: One of the channels which has clogged, this was for a salt concentration of 2mM and an applied potential of 20V.

I then, use a script that I have written, with which I can select the area of the channel. I do this for the inverted version of Figure 9. For the inverted image, a plot of the (light) intensity of the channel is made.

Using the plot of Figure 10, I can determine the starting position of the clogging very accurately. Because the intensity plot will rise very sudden at the location of the clog. When I know the starting location of the clog, I can easily determine the total length of the clog. By doing this for every used salt concentration and for every potential I can determine an accurate data-set of clog sizes for different parameters.

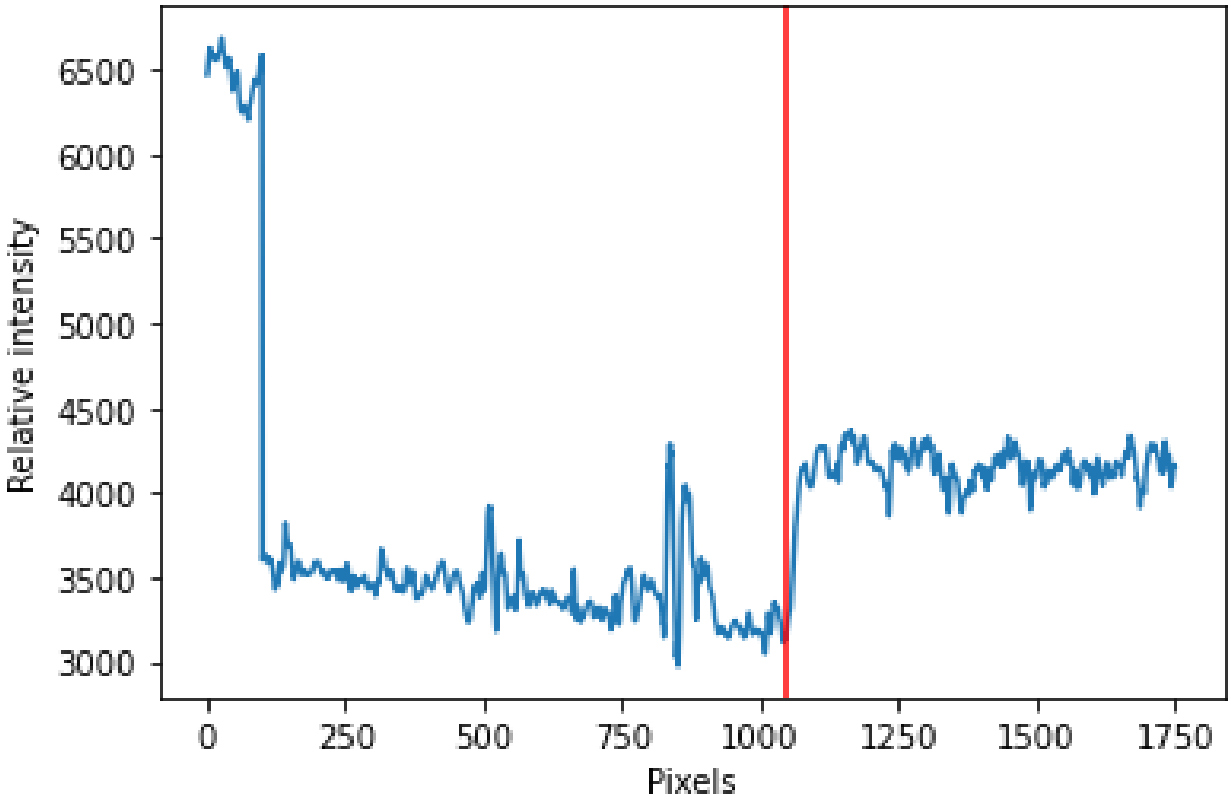


Figure 10: Plot of the light intensity of the channel in Figure 9 The vertical red line indicates where the clogging starts.

5.4.2 Flow velocity

I use Trackpy to determine the flow velocity of the particles inside the channel. With Trackpy I can easily select the particles in a defined area. These particles will be encircled, as can be seen in Figure 11

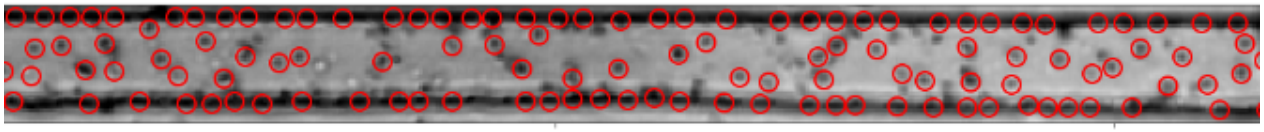


Figure 11: Display of a channel filled with particles. The encircled particles are selected by the tracking program.

The encircled particles are tracked followed throughout the frames and Trackpy plot their trajectories. An example can be found in Figure 12

The vertical trajectories in Figure 12 are not really particles that are moving upwards. When Trackpy finds a particle, it selects an area in which it will search for that particle in the next frame.

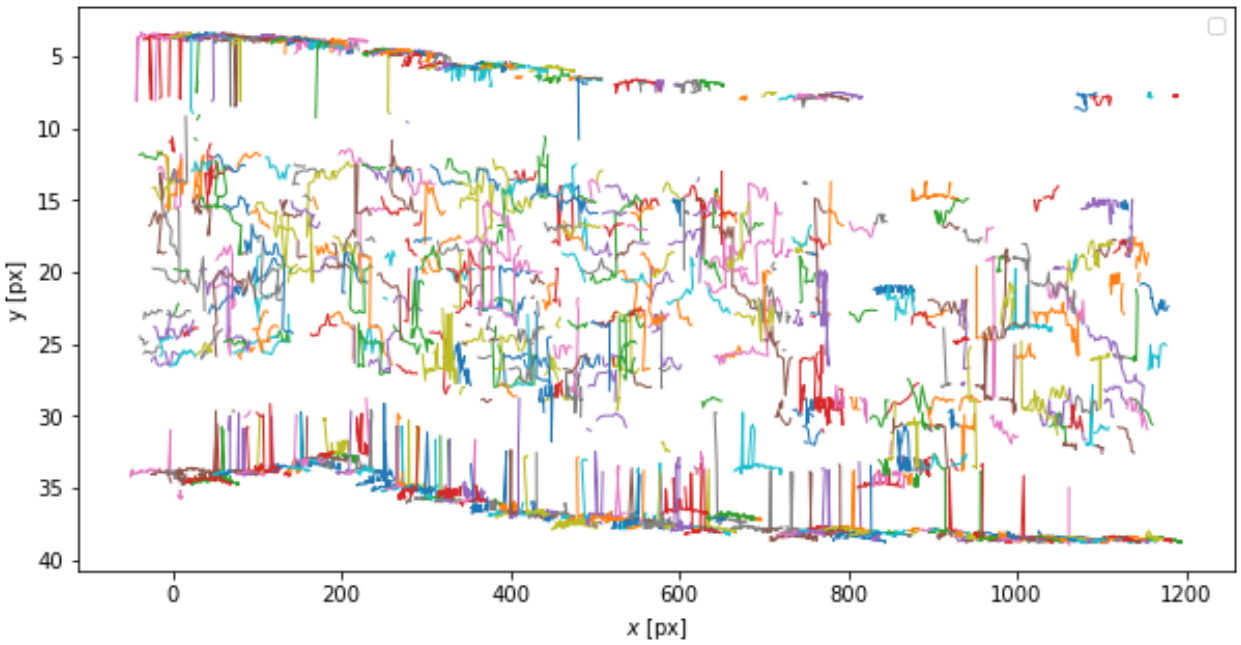
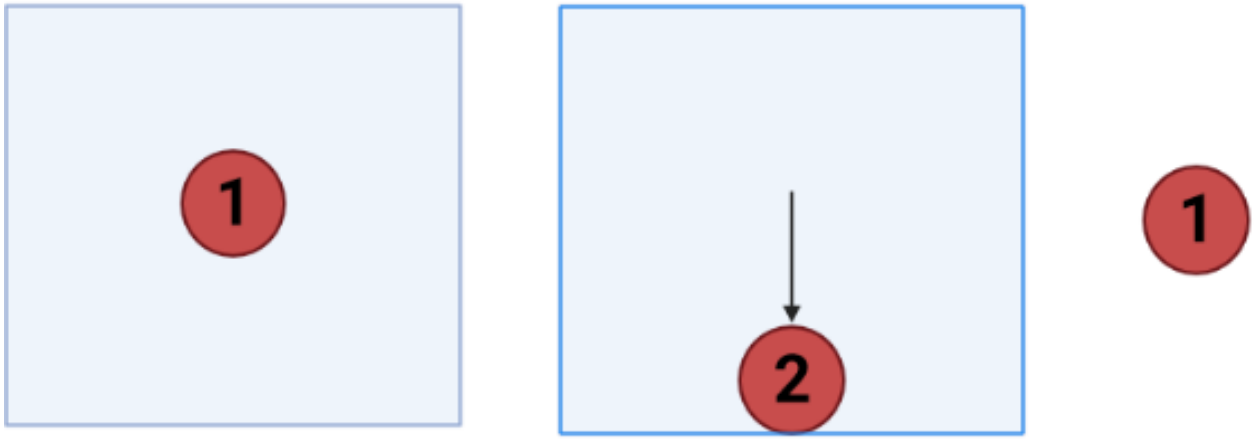


Figure 12: The trajectories of all the tracked particles. Every colour indicates a particle.

When the selected particle has left the area but a new particle has entered the area, Trackpy thinks that the new particle is the old particle and calculate the trajectory between these particles. Figure 13 shows a schematic display of this process.



(a) Trackpy selected a particle and area around it in frame 1. Trackpy will search for this particle in this area in frame 2

(b) The second frame. The original selected particle has left the search area and a new particle has entered the search area. Trackpy thinks that arrow is the trajectory of particle one.

Figure 13: Schematic display of the origin of the vertical lines in Figure 12.

For all the these trajectories, Trackpy plots the drift of the flow in the x- and y-direction. Then a linear fit runs through the drift in the x-direction and the slope of this fit gives me the flow velocity. Figure 14 gives an example of this drift plot.

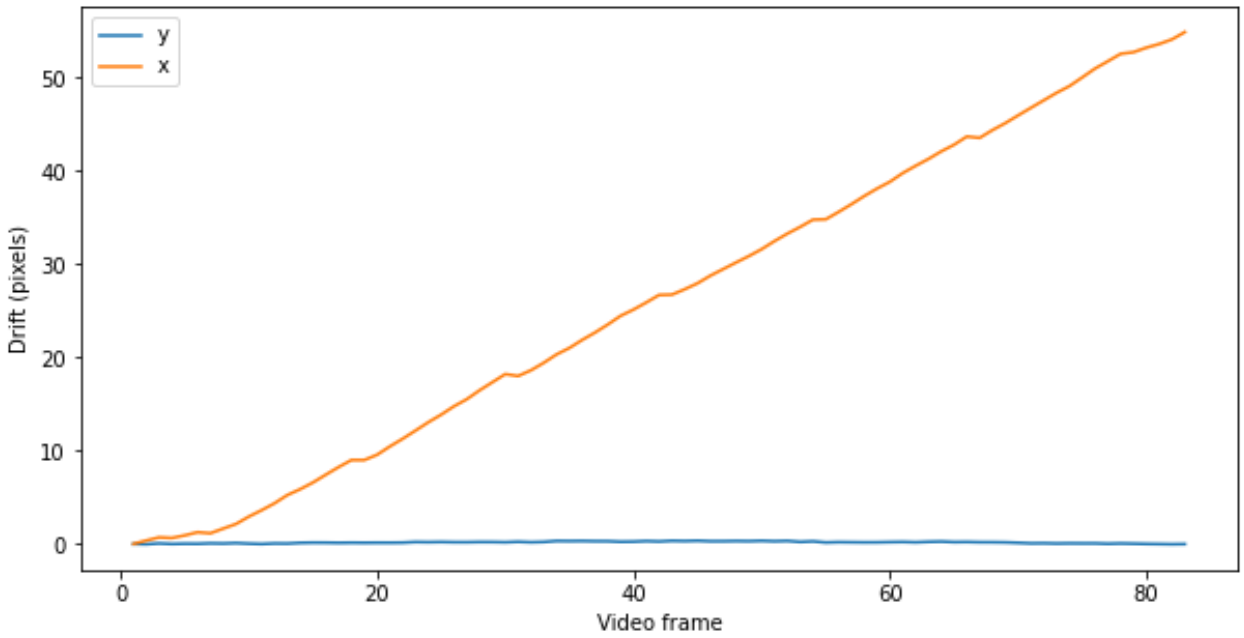


Figure 14: The Drift of the flow of particles. This plot is for a 2mM salt concentration and a 10V potential.

5.4.3 Current through channel

The data processing for the calculation of the current through the channel is more straightforward. I take the measurements that I made and plot those for the applied potential. I than use scipy to plot a linear fit through all the data points.

5.5 Results

5.5.1 Clogging of the channel

I did not observe any clogging during the measurements. As can be seen in Figure 15. Which is rather strange because during the testing phase clogging did occur. The channels clogged for every used parameter during the testing phase. However, clogging did not occurred systematically for a fixed set of parameters. So clogging occurred for every applied potential and salt concentration. However, when I repeated a measurement for a certain salt concentration and potential clogging did occur one attempt but not for the second attempt. Clogging did occur ±50% of the attempts during the testing phase when I used the press. Before I started using the press (so the only attachment between the glass and PDMS came from the activated Si-OH groups.), clogging occurred ±10% of the the attempts. The results of the testing phase were purely as a test to check whether my method was useful. However, I also saved the results of the final test and during this test measurement, clogging did occur. The results of these test measurements can be found in Table 3

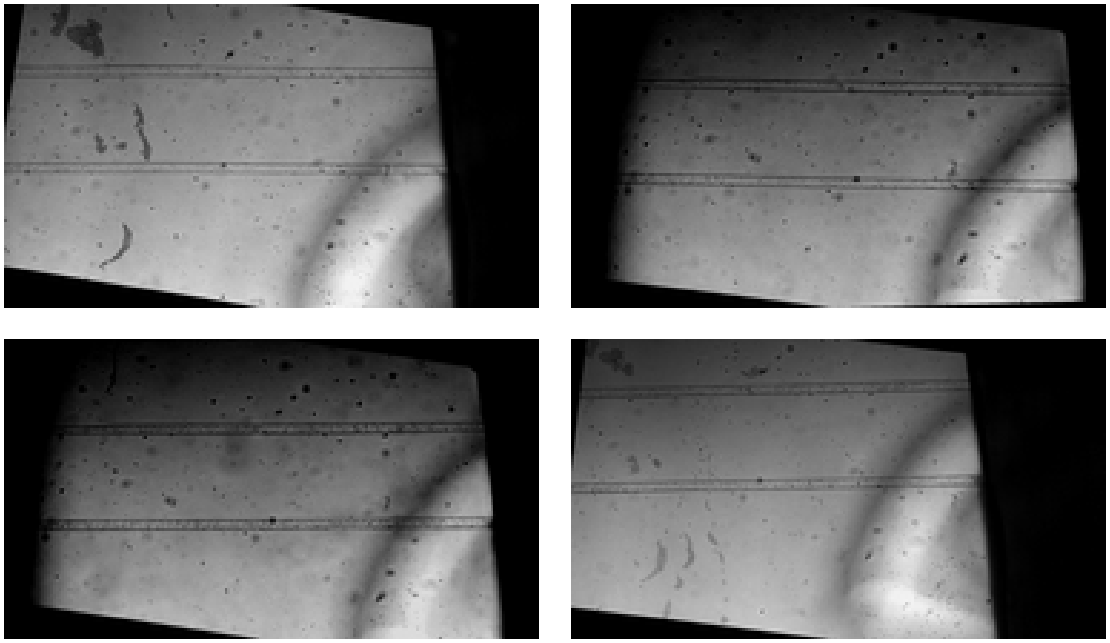


Figure 15: The channels after 30 min.
Upper left: 8mM, 50V. Upper right: 8mM, 1V.
Down left: 4mM, 20V. Down right: 2mM, 20V.

Parameters	Starting pixel	Ending pixel	Physical distance (μm)
2mM, 20V (upper)	1807	1043	582.9
8mM, 20V (upper)	1693	785	692.8
8mM, 20V (lower)	1598	617	748.5

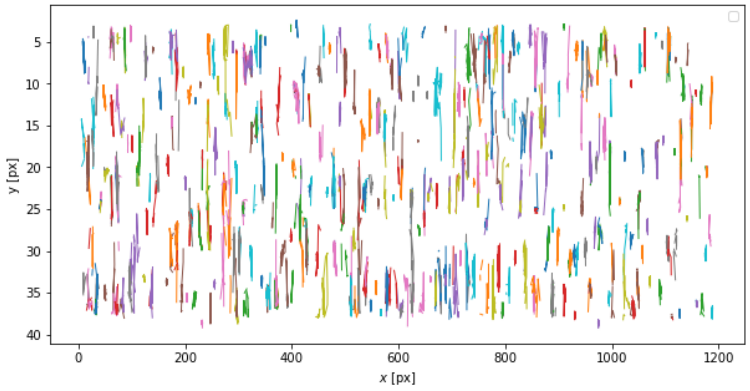
Table 3: Length of clogs in channels during the final test before the measurements.

5.5.2 Flow velocity

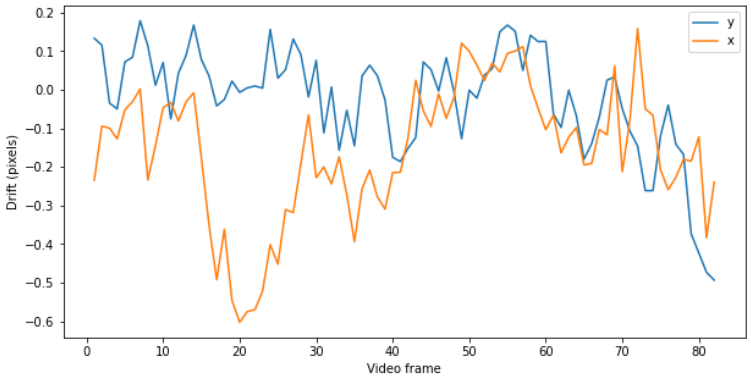
The calculations on the flow velocity are very unreliable. That is because the fps rate of the camera is too low for high salt concentrations and potentials. The particles are simply moving too fast for the camera. Which results in very strange trajectories and slopes, as can be seen in Figure 16a and Figure 16b.

The process described in Figure 16 already happens from a 20V potential for a 2mM salt concentration. As well as for the whole dataset of a 4 and 8 mM salt concentration. So Figure 17 only contains 6 datapoints[5].

[5]One sample contains two channels so there are 6 datapoints instead of 3.



(a) The trajectories of particles where the particles are moving to fast for the camera and Trackpy.



(b) The resulting drift of the flow through the channel where the particles are moving to fast.

Figure 16: Display of the trajectory and drift through a channel with a 4mM salt concentration and 15V potential.

5.5.3 Current through channel

The results of the current through the channel are in contradiction to those of the flow velocity complete and as expected. They can be found in Figure 18.

6 Discussion

6.0.1 Clogging of the channel

I got a multitude of results, some expected and some unexpected. The unexpected results originate from Section 5.5 and can have many reasons. I do not think that the applied potential is the cause of the absence of the clog. The reason for this is that one can visually check whether the liquid inside the channel is responding to the applied potential. A reason could be that the salt gradient was not steep enough. This could be caused by the press or sample that I used. As said before I use one sample multiple times before making a new sample. It could be that some salt was still in the channel somewhere which caused the salt gradient to collapse. However, this is

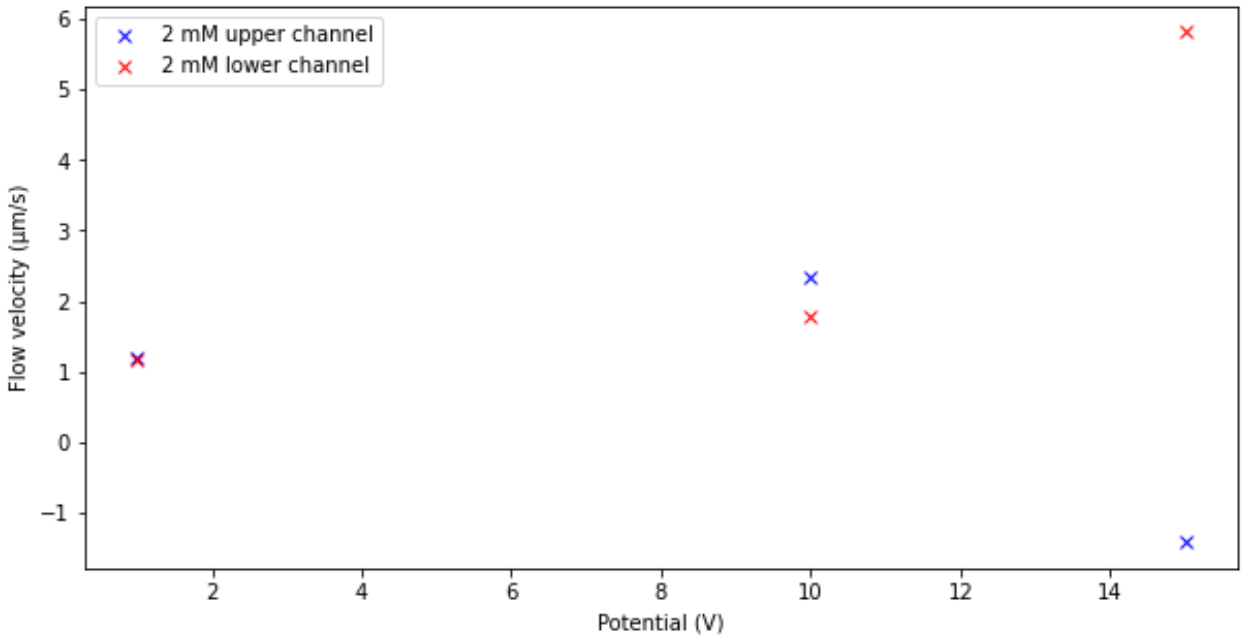


Figure 17: Plot of the flow velocity vs the applied potential. The upper and lower channel corresponds to the upper and lower channels of Figure 15.

just speculating because one can't visually check the salt concentration in the channel, the salt is transparent for the microscope.

Another cause could be that the DI water that I used was diluted. It could also be the case that the supersonic bath was diluted. Even though I change the water in the bath everytime I used it, it could still be that it was not clean enough.

A difference between the test measurements and the real measurements was that I used another batch of PDMS channels. So it could also be the case that the channels were already diluted. It is known that the PDMS channels are hydrophobic, so it's possible that the diffusio-osmotic flow is held back for these channels.

It is also difficult to balance the pressure between the two swimming pools. Because the pressure in the swimming pool is very sensitive to how much liquid one adds to these swimming pools. So it could be that you are seeing a flow of particles, but that it is mostly pressure-driven which will result in a 'false-positive flow'.

6.0.2 Flow velocity

The results for the flow velocity were also not as expected but are easier to explain. As said before, the frame rate was not high enough for Trackpy to follow all the particles. Which gave strange trajectories, drift plots and eventually flow velocities. So that is actually the process described in Figure 13. Another important thing to consider for this experiment is that I treat the particles as if it is in a two-dimensional world. While, it is in fact, three-dimensional. The most important

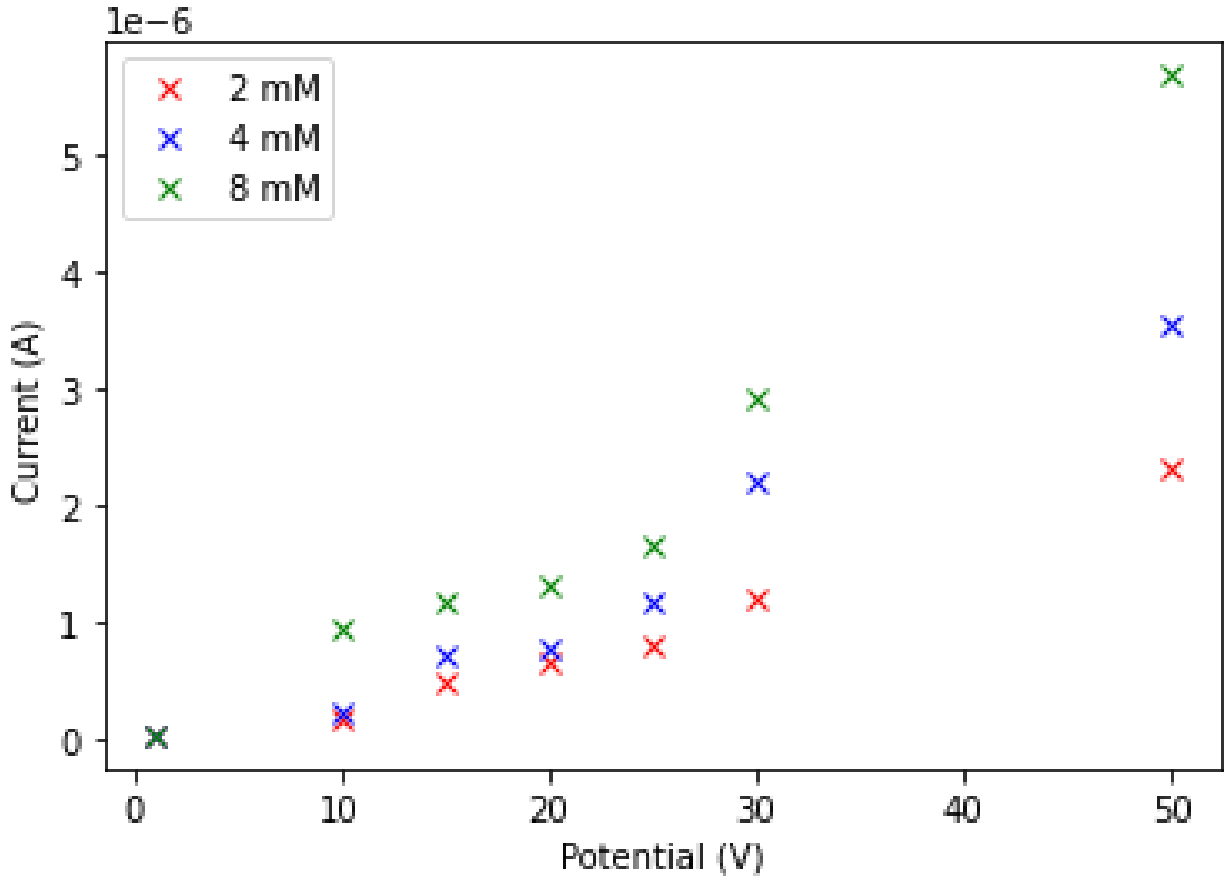


Figure 18: Plot of the current through the channel vs the applied potential for different salt concentrations.

difference is that it can seem as if particles 'overlap', which will cause problems for tracking.

6.0.3 Current through channel

The results for the current through the channel were as expected. I expected that for a larger potential/salt concentration, the current through the channel would also be larger, and Figure 18 shows exactly that. However, it is difficult to measure the exact current because it increases constantly during the measurement. I handled with this problem by doing the current measurement at a fixed time during the measurement.

7 Conclusion

The aim of this experiment was to determine how far a clog of particles would grow inside a micro-channel for different salt concentrations and applied potentials. In which I did not succeed. I believe that my method and setup were good because during the test measurements, I have seen clogging sometimes. I therefore think that it should be possible to perform this experiment with the expected results. However, I think that some things need to change for a follow-up experiment.

A lot of benefit can be gained by controlling the pressure more accurately. In my experiment it was difficult to find this equilibrium because I had to add the liquid by hand. I therefore think that there are better, more accurately ways to add the liquid to the swimming pool.

In future work, it is also important that the researchers find a way to measure the salt concentration inside and at both ends of the channels. In this way, they can see whether they need to make the salt gradient steeper or that it is steep enough. By doing that, they would also know whether there is any salt flowing through the channel. It would also help to place a hydrophilic coating on the PDMS channels. Sometimes it happens that none of the liquid got into the channel because the channel was simply to small. Making the channel more hydrophilic instead of hydrophobic would solve this problem.

As far as for the flow velocity and particle tracking, the future researchers need a camera with a higher fps rate. In this way, they would get flow velocity results for higher salt concentrations and potentials. It would also help if they use a better computer which can handle a larger search range so that less particles 'get lost'. As far as for the overlap problem, they can use a lower particle concentration. However, by lowering the particle concentration, clogging is also less likely to occur. Or at least the clog will grow slower.

I would also advice the future researchers to do measurements for potentials with smaller steps. The salt concentrations go logarithmic and I think that the log of 2 is a good parameter to use. However, using smaller steps for the potential values would give more accurate values for the flow velocity and give a better fit for the current through the channel. It would also give better results for the growth of the clog, if they succeed at seeing this.

In future research, I would also do more measurements for the current through the channel. By not simply perform one current measurement per sample at a fixed time. But make more current measurements per sample at different times. In this way, researchers can see how the current is increasing inside the channel. With this they can say something about the slope of the increase in the current.

I did not do much measurements because of time sake. It took me a long time and a lot of testing before I started measuring because there were a lot of setbacks. To give two examples: I started using the press after a long time of testing it without it but it turned out that the attachment of the PMDS to the glass was to weak. I waited so long with the press because it was a time investment of which I had doubts whether it would work and was worth the time. Another common problem was that the liquid did not flow inside of the channel because the channels were just to small. This seemed a measure of chance but with the press it got easier to control this because I could also 'lift' the PDMS from the glass causing the DI water to flow into the channel. I should have used the press a lot earlier in hindsight.

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