Supporting information: Material- and size-selective separation mechanism of micro particles in frequency-modulated dielectrophoretic particle chromatography

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ABSTRACT

Separation of (biological) particles ($\ll 10\,\mu m$) according to size or other properties is an ongoing challenge in a variety of technical relevant fields. Dielectrophoresis is one method to separate particles according to a diversity of properties, and within the last decades a pool of dielectrophoretic separation techniques has been developed. However, many of them either suffer selectivity or throughput. We use simulation and experiments to investigate retention mechanisms in a novel DEP scheme, namely, frequency-modulated DEP. Results from experiments and simulation show a good agreement for the separation of binary PS particles mixtures with respect to size and more importantly, for the challenging task of separating equally sized microparticles according to surface functionalization alone. The separation with respect to size was performed using $2\,\mu m$ and $3\,\mu m$ sized particles, whereas separation with respect to surface functionalization was performed with $2\,\mu m$ particles. The results from this study can be used to solve challenging separation tasks, for example to separate particles with distributed properties.

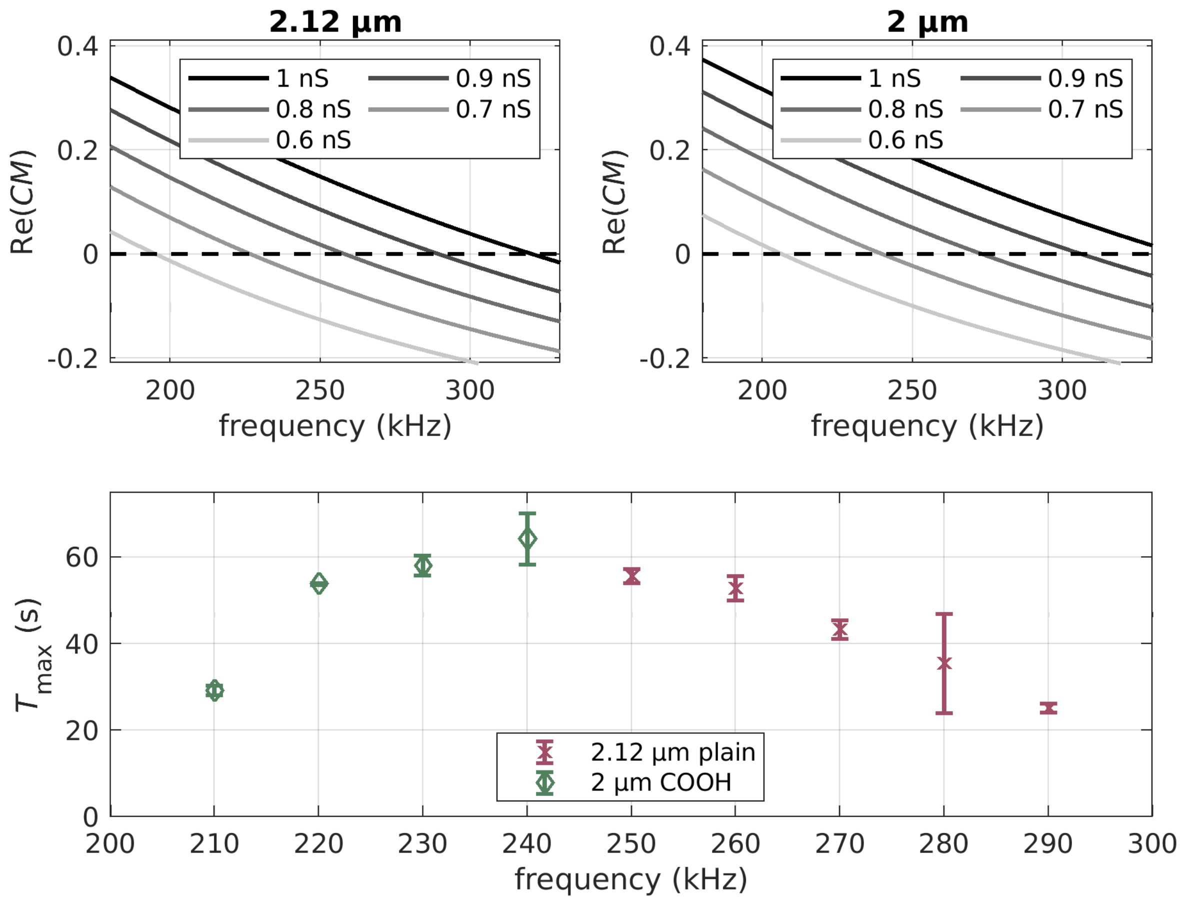

Figure 1. Top: Calculated values of the real part of the Clausius-Mossotti equation for different surface conductances. $d_\mathrm{p} = 2\,\mu\mathrm{m}$ PS particles with a carboxy functionalization and $d_\mathrm{p} = 2.12\,\mu\mathrm{m}$ PS particles without functionalization in a $2\,\mu\mathrm{S\,cm^{-1}}$ suspension. Bottom: Maximum of the residence time distributions for different frequencies.

1 Fixed-frequency data

For the plain 2.12 µm and the carboxylated 2 µm particles results of the fixed-frequency measurements are displayed in figure 1. The best match between the experiments with no applied voltage and an voltage at fixed frequency was found at 290 kHz resulting in an surface conductance of $K_\mathrm{s} = 0.9\,\mathrm{nS}$. In contrast to the plain particles, the carboxylated 2 µm spheres show a much lower crossover frequency (figure 1). This results in a measured crossover of $K_\mathrm{s} = 0.6\,\mathrm{nS}$. Without applied voltage the particles elute at 27.5 s.

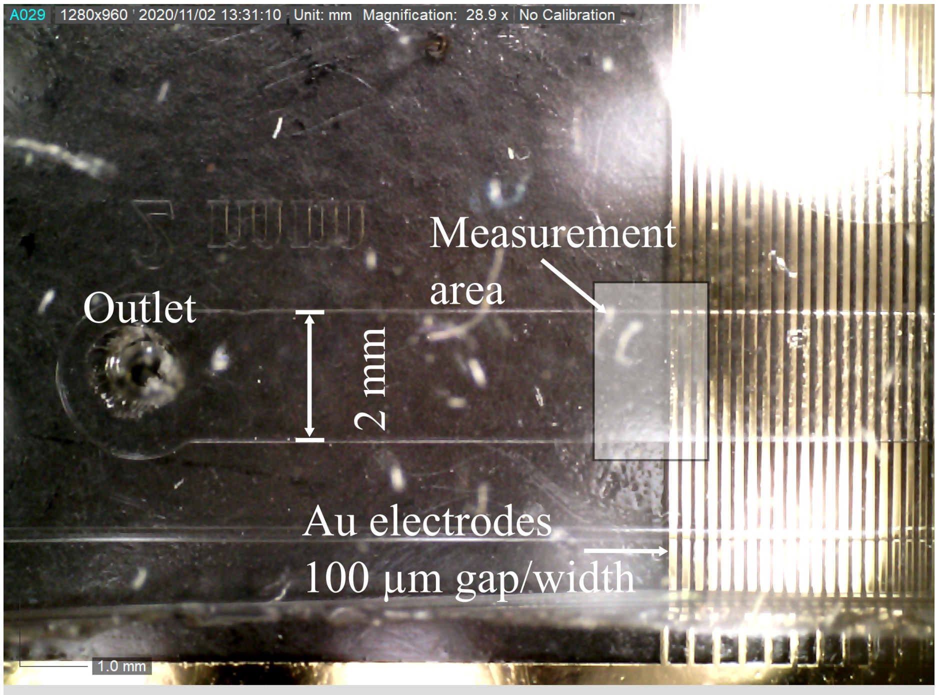

Figure 2. Photograph (digital microscope) of the channel with important parameters of the set-up.

2 Experimental Set up

An image from a digital microscope of a section of the device is given in figure in 2. The videos for the calculation of the residence time distributions were recorded in the measurement area. This area is close to the outlet and right behind the last pairs of electrodes. Since an inverted microscope was used, videos were recorded from below the channel filming through the electrode chip. After the recording the video was compressed using ffmpeg and segmented with Matlab.

On top of the electrodes the thin PDMS layer produces a high-pass filter effect which can be simulated in COMSOL. For various thicknesses (figure 3) this effect could observed in the simulation. However, since the lowest frequency in the manuscript was 90 kHz no significant influence is to be expected in the experiments. The effect was implemented by multiplying the electric field with a frequency-dependent fit function so that $E = g(f) \cdot E_0$. $g(f)$ is determined through $g(f) = 1 - \exp^{-8.013e-5 \cdot f}$, with f the electric field frequency.

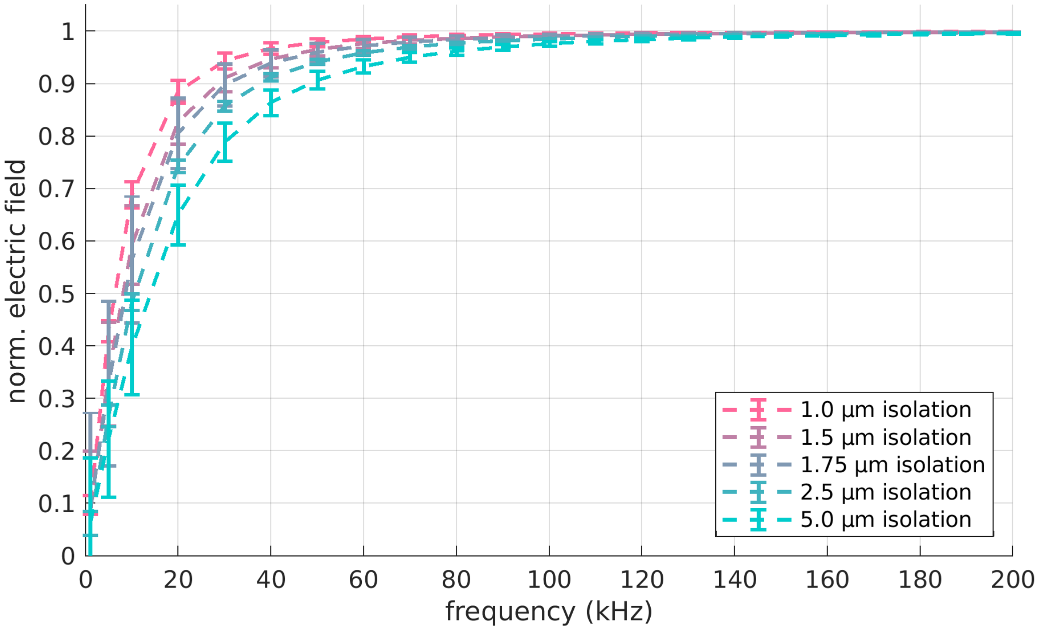

Figure 3. Normalized electric field strength of mesh points for various isolation thicknesses of a representative area (400 µm x 80 µm). The intensity of a point is normalized to the value of that point at 300 kHz. The standard deviation provides information about how different the single points are affected by the high-pass filter effect.

3 Results

The maximum of the peaks matches well as shown in the main document. As described before, the simulated peaks of the 3.1 µm particles are more narrow than they are in the experiment, as soon as the particles experience a retardation due to nDEP dominated movement. This can be seen in figure 4. However, when the nDEP/pDEP ratio is balanced, experiment and simulation show a good agreement. Figure 5, which displays the full width at half maximum (FWHM) values for the 2.12 µm particles, shows a better match for experiment and simulation. Except for one case ($f_\mathrm{c} = 210\,\mathrm{kHz}$ and $V_\mathrm{pp} = 80\,\mathrm{V_{pp}}$), where in the simulation significant peak broadening becomes visible (large FWHM). In this case the small 2.12 µm particles do not show sufficient particle movement away from the electrodes in the simulation when they experience nDEP due to the low applied voltage and centre frequency. In reality in contrast, the particles are able to elute from the channel faster. This might be due to the freeze boundary condition in the simulation which seems not to be always valid for the particles. However, in general the FWHM values of the smaller particles are much lower than of the 3.1 µm particles. We assume, that this is because of the strong DEP close to the electrodes which might suppress other effects and leads to a movement dominated by dielectrophoresis.

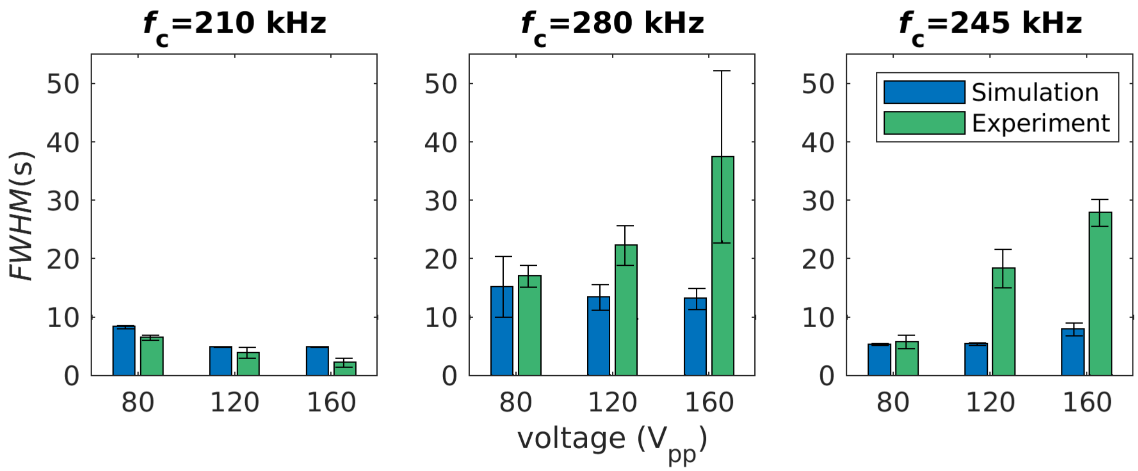

Figure 4. Full width at half maximum for the plain 3.1 µm at different centre frequencies and voltages. Both, simulation and experiments were conducted 5 times to check for statistical validity.

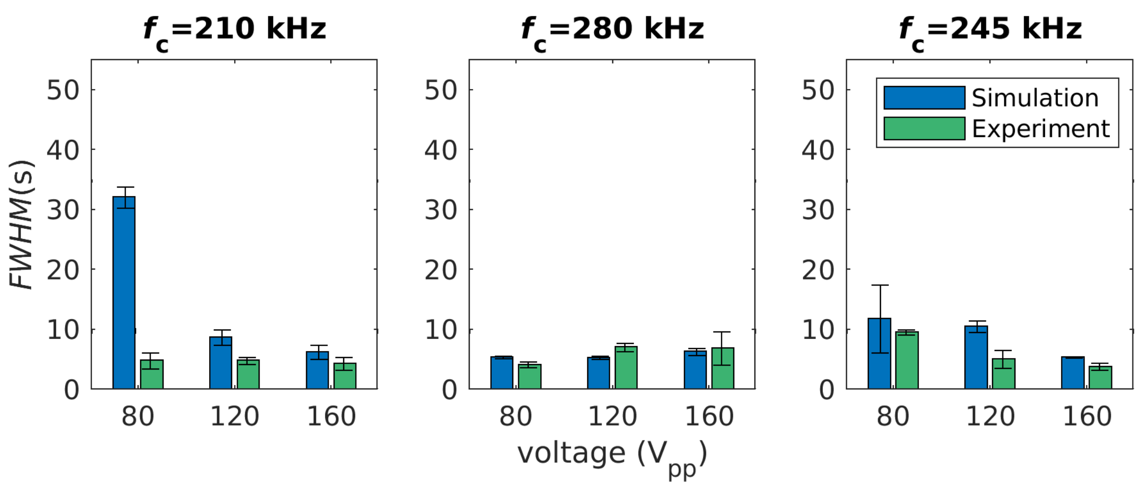

Figure 5. Full width at half maximum for the plain 2.12 µm at different centre frequencies and voltages. Both, simulation and experiments were conducted 5 times to check for statistical validity.

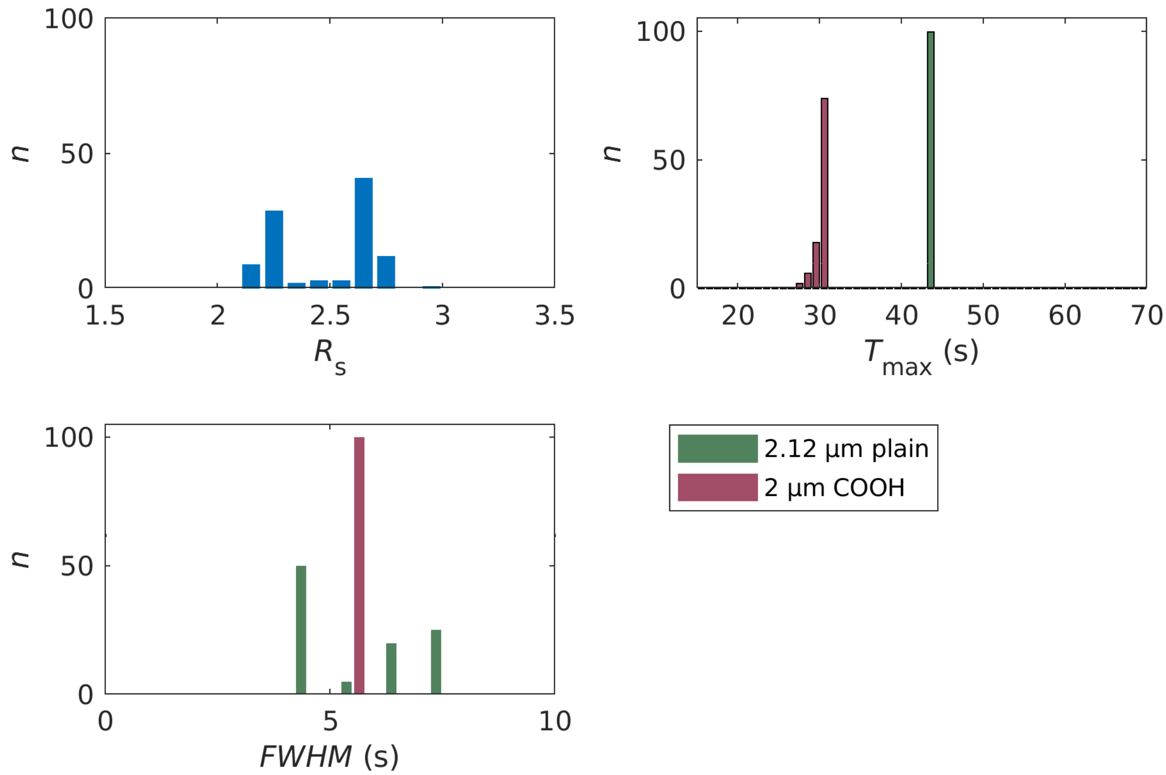

Figure 6. Statistical analysis of a separation of 2.12 µm plain particles and 2 µm carboxy particles at 160 V_{pp}, frequency window 90 kHz to 330 kHz (centre frequency 210 kHz) and a modulation frequency 300 mHz. Top left: bar plot of the resolution. Interval size is 0.1. Top right: distribution of the position of the maximum of the peaks. Bottom left: Full width at half maximum (FWHM) distribution of the simulation data. Interval size for $T_{\max}$ and $FWHM$ is 1 s.

4 Simulation

The simulation contains mainly two random parameters. First, the 200 particles per species are randomly distributed in the inlet area in the simulation. Second, the release offset the particles get, as soon as the crossover frequency is reached during the simulation. We conducted 100 simulations with the very same particles and selected a case witch showed a distribution of resolutions. The selected case was the material selective separation with a centre frequency of 210 kHz at 160 V_{pp}. The distributions of resolution, of the maximum of the peaks and the full width at half maximum (FWHM) are shown in figure 6. The position of the maximum of the peaks only varies slightly, whereas the FWHM values of the 2.12 µm show a variation. Because of their longer residence time in the channel more distributed elution times become more likely due to the stochastic character of the simulation. This variation is the reason for the distribution of the resolution and shows the importance of conducting multiple simulations for the same parameter to generate statistical validity.