

Concentration Polarization to Measure the Nanopore Accessibility of FCC Particles

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Abstract:

Fluid catalytic cracking (FCC) particles are an important catalyst for the oil refinery processes. The porous structure of these particles enables large feedstock molecules into the catalyst domain, where they are cracked into smaller hydrocarbons. Deactivation of FCC particles happens by accumulation of the metal atoms Fe, V and Ni in the nanopores of the catalyst domain. Fe, V and Ni are the residue of the cracking process and settle inside the pores, stacking over time and eventually blocking the pores (Figure 1). As the particles age, the density of the FCC particles

increases by the stacking of Fe, V and Ni in the nanopores, corresponding to an effective decrease in the nanopore-sizes.

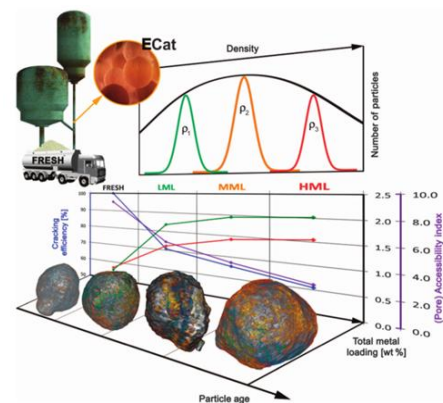


Figure 1 - FCC deactivation over time

In this study, ionic concentration polarization (ICP) effects are measured for different densities of FCC particles. First particles of similar density fractions will be used to measure differences in ICP effects for different concentrations. When the boundary region of ICP effects is found, meaning the region in which ICP effects are barely observable to the region in which these are not observable, the limit of the concentration for these ICP effects will be approached to measure differences in ICP effects for the different density fractions. When there are differences in ICP for the different density fractions of FCC particles, the ICP effects will vary more when the limit of ICP is approached. PDMS chips are made (Figure 2) to accommodate the use of fluorescence microscopy (Figure 4) to study the ICP effects.

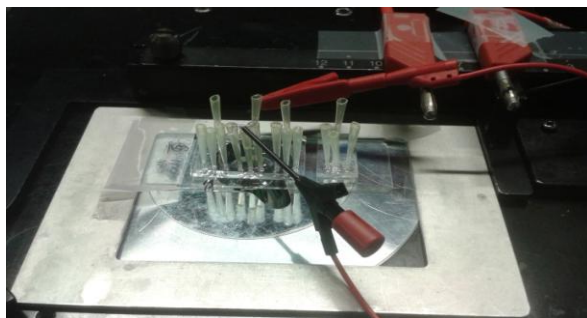


Figure 2 - Connection of platinum electrodes to the inlet and outlets of one PDMS chip

This study reveals that differences in ICP can indeed be measured for different concentrations of electrolyte (Figure 3). Furthermore, there are inconsistent differences measured in ICP between the different density fractions of FCC particles, implying that ICP cannot be used to measure the nanopore accessibility of FCC particles.

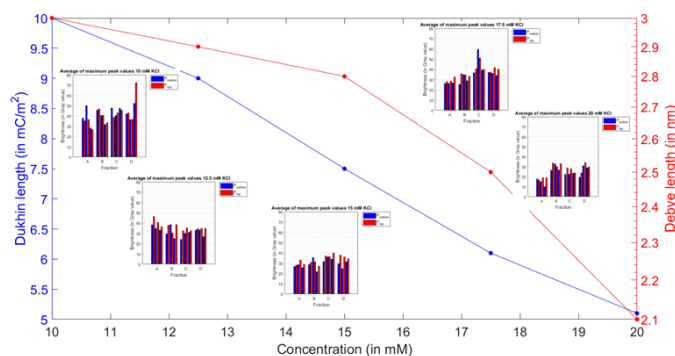


Figure 3 - Experimental results

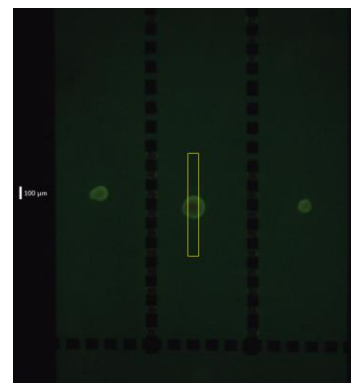


Figure 4 - Fluorescent microscopy image, the yellow box indicates the region taken for data analysis

Concentration Polarization to Measure the Nanopore Accessibility of Fluid Catalytic Cracking Particles

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Abstract

Fluid catalytic cracking (FCC) particles are an important catalyst for the oil refinery processes. The porous structure of these particles enables large feedstock molecules into the catalyst domain, where they are cracked into smaller hydrocarbons. Deactivation of FCC particles happens by accumulation of the metal atoms Fe, V and Ni in the nanopores of the catalyst domain. Fe, V and Ni are the residue of the cracking process and settle inside the pores, stacking over time and eventually blocking the pores. As the particles age, the density of the FCC particles increases by the stacking of Fe, V and Ni in the nanopores, corresponding to an effective decrease in the nanopore-sizes. In this study, ionic concentration polarization (ICP) effects are measured for different densities of FCC particles, which is related to the effective nanopore size. First particles of similar density fractions will be used to measure differences in ICP effects for different concentrations. When the boundary region of ICP effects is found, meaning the region in which ICP effects are barely observable to the region in which these are not observable, the limit of the concentration for these ICP effects will be approached to measure differences in ICP effects for the different density fractions. If there are differences in ICP for the different density fractions of FCC particles, the ICP effects will vary more when the limit of ICP is approached. This study reveals that differences in ICP can indeed be measured for different concentrations of electrolyte. Furthermore, there are inconsistent differences measured in ICP between the different density fractions of FCC particles. This implies that ICP cannot be used to measure the nanopore accessibility of FCC particles.

1 Introduction

In the oil refinery industry, the cracking process of crude oil into useful hydrocarbons is being done by a catalyst inside so called fluid catalytic cracking (FCC) particles. FCC particles have a heterogeneous porous structure through which the large feedstock molecules are led into the catalyst domain where the splitting takes place. It is known that accumulation of metal atoms such as Fe, V and Ni deactivate FCC particles by (partial) blocking the nanopores of the particle.^[1, 2] The blocking of the nanopores or the deactivation of the FCC particle is proportional to the amount of processes the FCC particles undergo, also known as ageing of the particle. A conservative measure for the average lifetime of a FCC particle in the oil refinery industry is 1 month. However, in the oil refinery industry it is not possible to selectively remove the deactivated catalyst, therefore a small portion of the catalyst material is removed and refreshed on a daily basis. For efficient use of these catalysts, it is useful to have information about the state of the FCC particles, so that they are not dumped while still being fresh, active catalysts. Information as the effective pore size at any given interval during the catalytic process is therefore of great importance.

There are several existing methods to tailor the nanopore structure of zeolites, which are the main cracking components of FCC particles. *K. Kant et al.* studied the dependence between the electrical properties of nanoporous arrays and the nanopore size of these arrays.^[4] The nanoporous structure of zeolites, a fundamental structure of FCC particles, can be

tailored by confocal fluorescence microscopy.^[5] *A. L. Myers* proposed equilibrium thermodynamic experiments to characterize nanopores by introducing constants for both the standard enthalpy and the entropy of adsorption of probe molecules.^[6]

There is no work published about a method using ionic concentration polarization (ICP) to measure the nanopore size of FCC particles, even though ICP effects have been observed for nanoporous structures with different electrical double layers (EDLs). An example of this is the rapid ionic concentration polarization (ICP) transport phenomena observed inside a thin Nafion film, acting as a nanoporous channel in a microfluidic chip.^[7]

Before motivating why ICP is a possible way to measure the nanopore accessibility of FCC particles, the fundamental concept of ICP has to be given. Suspended particles have an electric surface charge, on which an electrostatic Coulomb force is induced through application of an external electric field. The double layer theory states that all surface charges in fluids are screened by a diffuse layer of ions, this layer of ions has the exact opposite charge with respect to the surface charge such that the total electrical double layer (EDL) that is formed, maintains charge neutrality. For porous particles like FCC particles, charge-selective transport occurs in pores where the EDLs are thick enough and are slightly overlapping, see figure 1.

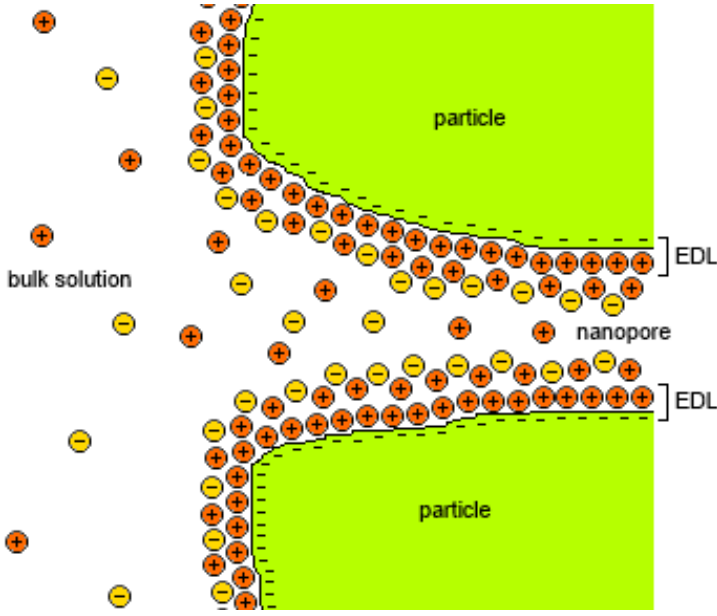


Figure 1: Example of a suspended porous particle in an electrolyte solution

In the case where charge-selective transport occurs, counter-ions are enriched in the nanopore and co-ions are excluded. The electric field along this charge-selective nanopore is used to induce ICP at its boundaries to the microfluidic channel. At the anodic side of the particle, a depletion region is then formed and at the cathodic side of the particle an enrichment region.

The dependence between ICP and the nanopore diameter can be described by the Dukhin number, a dimensionless number that relates the surface conductivity of the EDL to the bulk conductivity of the electrolyte.^[3] The inverse Dukhin number, shown as the ratio on the right-hand side in Equation 1, relates the ratio of the bulk conductivity of the electrolyte over the surface conductivity of the EDL to the nanopore diameter, bulk concentration of the electrolyte and surface charge of the EDL.

$$\frac{G_{bulk}}{G_{\sigma}} \approx \frac{Fhz c_0}{\sigma} \quad (1)$$

, where G_{bulk} is the bulk conductance in $(\Omega m)^{-1}$, G_{σ} is the surface conductance in $(\Omega m)^{-1}$, F is Faraday's constant in J or C/mol , h is the nanopore diameter in m , z is the valency of the counter-ions, c_0 is the bulk electrolyte concentration in mol/L and σ is the surface charge of the EDL in $(\Omega m)^{-1}$.

Strong ICP effects typically happen for inverse Dukhin numbers much smaller than 1, where the Dukhin number is dominated by the surface conductance of the EDL and the EDLs of the nanopore are thick enough to be (partially) overlapping. However, strong ICP effects have been shown for inverse Dukhin numbers that are much smaller than 1, but with non-overlapping EDLs.^[8] It has not yet been shown in literature that this relation, in combination with ICP can be used to describe the nanopore sizes of FCC particles.

This research will focus on the differences in ICP for FCC particles that are affected by Fe, Ni and V. It has been shown in literature that if more of these metals have been accumulated in the FCC particle, thus the more metals are (partially) blocking the nanopores, the lower the nanopore accessibility

gets.^[1] In other words, the denser the particle by accumulation of Fe, Ni and V, the more the nanopores of the FCC particle will get (partially) blocked, decreasing the effective nanopore size. In this research it will be shown whether differences in nanopore size of FCC particles by clogging of Fe, Ni and V in the nanopores can be measured by differences in ICP. Theoretically, the smaller nanopore sizes through partial blockade would increase the ICP effects. The ICP effects can be observed by means of fluorescent microscopy. Changes in brightness would then be observable as negative fluorescent tracer gets attracted to the counter-ions in the electrolyte solution and moving along with them in case of ICP.

By means of fluorescent microscopy, first differences in ICP phenomena in FCC particles are observed for different concentrations of electrolyte, in which all further important conditions are the same, such as: particle density, electric field strength and time, type of electrolyte, microfluidic channel dimensions, concentration of fluorescence, photobleaching time and camera settings. As part of the setup, microfluidic chips are made to arrange the necessary condition of having suspended, stagnant FCC particles in an electrolyte solution. On this particle a homogeneous electric field needs to be applied. After differences in ICP phenomena are observed for different concentrations of electrolyte, ICP effects will be measured on particles with different densities, thus particles with different nanopore sizes. For this, concentrations of electrolyte are being used that are close to the boundaries of having ICP and no ICP. When approaching the limit of having ICP, if there are differences in ICP effects between different particle nanopore sizes, the differences in ICP effects for the different particle nanopore sizes will be larger near the limit of having ICP.

This paper will present this by the experimental setup and methodology that are used, followed by the results and discussion of the measurements and closes off with a conclusion and outlook on this research.

2 Experimental

As electrolyte, a KCl solution of $1 M$ was made and diluted into solutions of $100 mM$, $10 mM$ and $10 \mu M$. To $10 mL$ of these solutions, $5 \mu M$ BODIPY 492/515 disulfonate was added as fluorescent tracer. After the boundaries of ICP effects and non-ICP effects were roughly known solutions of $20 mM$, $25 mM$ and $50 mM$ KCl were prepared by diluting the remainder of the $100 mM$ KCl solution without fluorescent tracer. And to these solutions again $5 \mu M$ BODIPY 492/515 disulfonate was added. After this, KCl solutions of 17.5 , 15 and $12.5 mM$ were made, each also containing $5 \mu M$ BODIPY 492/515 disulfonate. The containers in which $10 mL$ of each solution was put, were covered with aluminium foil to prevent photo-bleaching of the fluorescence and stored in a freezer ($-5^{\circ}C$) for further use.

The PDMS chips are fabricated using standard PDMS fabrication techniques. For the first testings, the chips shown in appendix REF were used. For the final measurements with 10 , 12.5 , 15 , 17.5 and $20 mM$ KCl the chips shown in Figure 2 were made. These chips contain 1 inlet and 3 outlets, each outlet is connected to a channel which merge into a bigger

channel connected to the inlet. The 3 smaller channels and the bigger channel are separated by PDMS pillars. The channels of the chip are 200 microns deep, other chip dimensions are depicted as shown in Figure 2. Before bonding the PDMS to glass, 3 FCC particles are injected in the small channels of one chip, such that each small channel corresponding to 1 outlet contains 1 FCC particle of the same density. In order to inject the FCC particles, the FCC particles are put in a small box and suspended in deionized (DI) water. 1 particle with some DI water is then sucked up with a pipette and carefully injected in 1 channel, the excessive water in the channel is then sucked up again as much as possible and deposited in the box it came from. After injecting 4 chips, with each chip containing a different density of FCC particles, the chips are bonded to a single glass. During the plasma treatment, the remaining amount of water in the microfluidic channels gets evaporated in the vacuum. By putting in the FCC particles in the channels before bonding, the particles become stagnant particles due to the surface tension between the particles and the PDMS. The properties of the FCC particles are not affected by the plasma treatment.

In each of the inlets and outlets of the PDMS chips, 200 μL pipette tips are used as reservoirs. In order to prepare for the injections of electrolyte in the microfluidic channels before the measurements, 0.5 mL of solution is injected in a syringe and covered with aluminum foil to avoid photo-bleaching of the fluorescent tracer. The chips are prepared for testing by injecting the *KCl* solution in the reservoir through the inlet of the chip, depicted on the right side in Figure 2, and pushing the solution all the way through the chip until the 3 reservoirs at the outlets of the chip are filled. Due to the surface tension between the FCC particles and the PDMS the FCC particles in general do not move while injecting the electrolyte. The injections of *KCl* solution are done such that each glass containing 4 PDMS chips uses a single concentration of *KCl*.

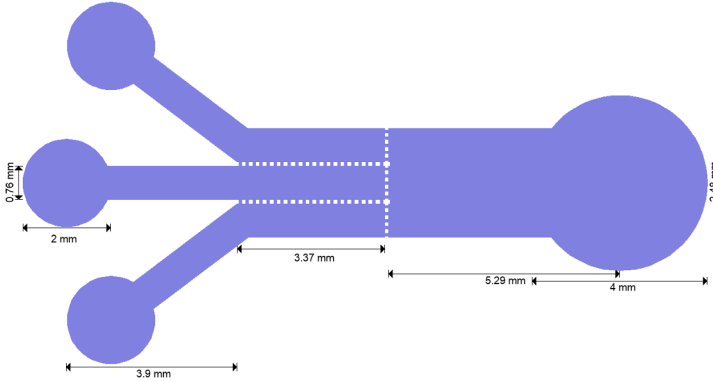


Figure 2: Single chip with dimensions

The measurement-setup to be used is as shown in Figure 3. For every measurement, the chips to be tested have to be covered to prevent both influence of white light in the experiment and photo-bleaching of the fluorescence. Blue camera light was applied a few seconds before starting each measurement. The fluorescent tracer inside the microfluidic chips is monitored by using a *Olympus IX51* microscope with CCD camera (*Grashopper 3 GS3-U3-23S6C*, *FLIR, Canada*). The following camera settings were used: the shutter time was set to 80.597 ms, the gain was 29.996 dB, the framerate 12.380 fps, W.B. (red) 614, W.B. (blue): 859. The coloring, W.B., on the camera recording corresponded to green light.

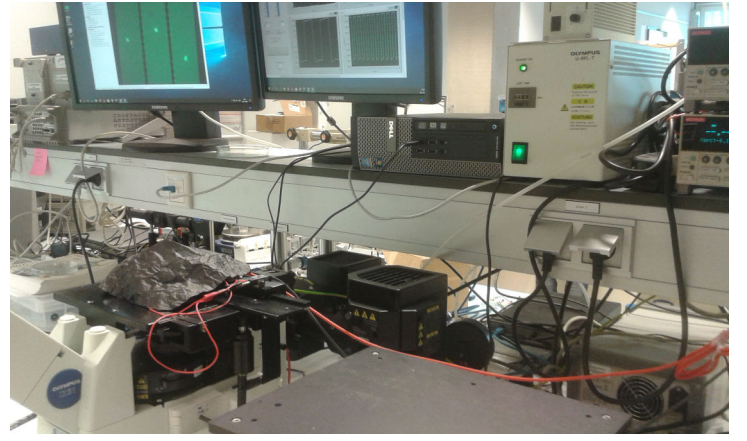


Figure 3: Measurement setup to be used for experiments

Electric potentials were applied at both ends of the channels by inserting a platinum wire with a 0.25 mm diameter in each reservoir. The 3 outlets of the chip are connected to one potential of the voltage supply and the inlet to the other, reference potential. *LabVIEW 2017* was used as software to make the voltage supply generate a square wave with amplitude of 100V, zero offset and frequency of 0.25 Hz. For each measurement these square waves were applied for 40 s. The upper limit of the current was set to 5 mA to prevent Joule-heating. Close to the limit of ICP, the current is proportional to the concentration, as the bulk electrolyte conductivity gets the dominant factor in the Dukhin number. Therefore, care has to be taken that the power dissipation through the microfluidic chip will not be too high as the temperature rise will affect the experiments. 500 mW of power is therefore the upper limit of power. The reasoning behind putting in the square waves is to prevent pH changes happening in the electrolyte. M-JPEG videos were made using the software *FlyCap2 2.11.3.121*, that simultaneously ran with the applied potential.

For further data analysis, a macro was ran on *ImageJ* to retrieve the brightness (in Grayscale value), position (in microns) and time (in frames) of the polarization regions of each FCC particle in the videos. The area selected of each particle for data analysis is as shown in Figure 4. The background fluorescence is also selected in order to subtract the background brightness later on from the brightness of the polarization. A wider rectangle is selected instead of a thin line to reduce measurement noise. The reasoning behind this is that transition between each pixel of the videos can be a bit distorted. The macro ran on *ImageJ* takes the average over this width. The width of the rectangle is taken such that the depletion regions at the sides of the particle are not selected, see Figure 4.

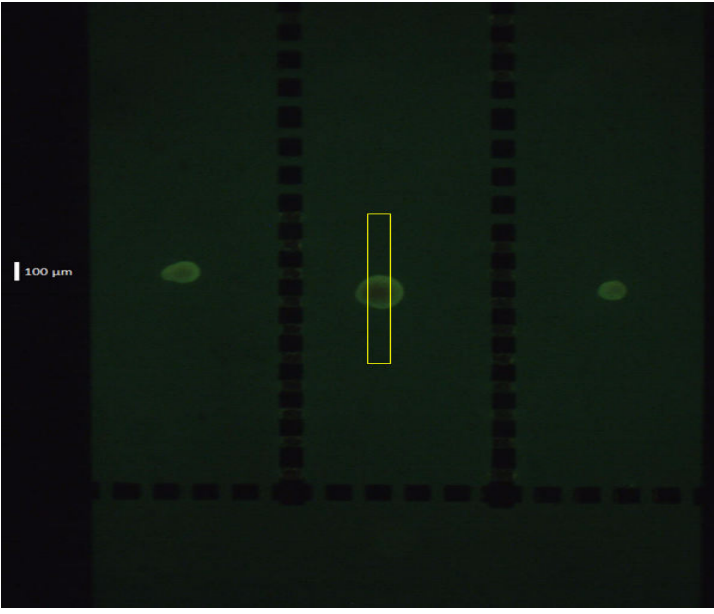


Figure 4: Single chip with dimensions, units are in microns

After retrieving the data, the data is analyzed using *Matlab*. A .m-script is written for *Matlab* to make a surface plot of the data, plotting the time, position and brightness on separate axes, see Figure 5. For this, the time in frames and the position in pixels are first converted to time in seconds and position in microns. Next, the script separates the data into two matrices, each matrix containing 1 enrichment region of polarization of a FCC particle. In Figure 5, these polarization regions can be seen as the two rows of peaks at the position axis. After this separation, the script finds the single maximum value of each matrix with its index number, where the index number corresponds to the row of its position. This index number is subsequently used to find and plot the maximum row of peaks in each polarization region, shown in Figure 6. After this, the script separates the rows of peaks into different regions, shown in figure 7, with each region containing one peak. Each peak of polarization corresponds to each rise in amplitude of the square wave applied in the measurements. Next, the maximum value of brightness in each region is found, added and from this the average is taken. From this average, the background brightness is subtracted. After these numbers are found for all different particles in the chips on 1 glass, the results are plotted in a single bar graph per concentration of *KCl*.

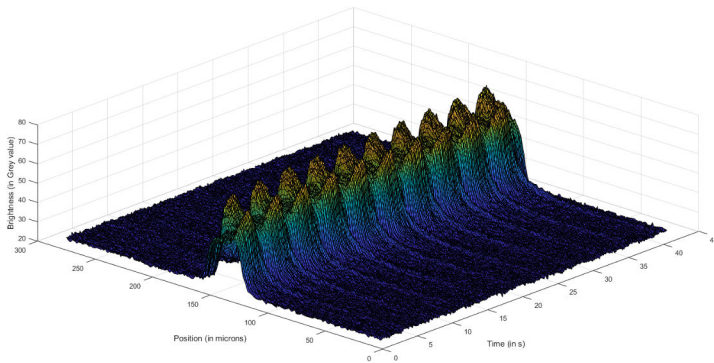


Figure 5: Surface plot of the brightness of the FCC particle versus the position versus the time

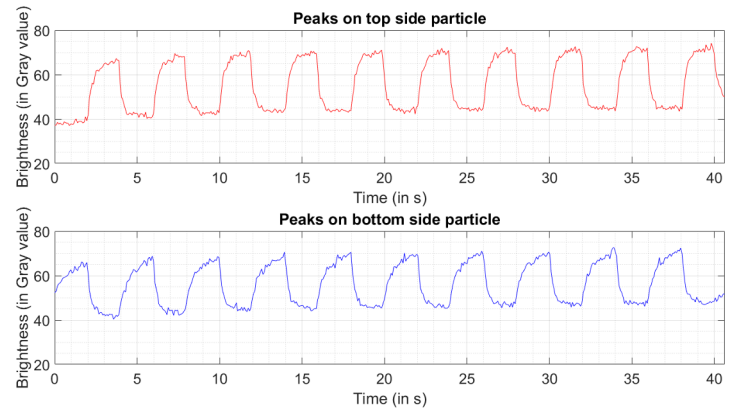


Figure 6: Separation of rows of maximum peaks per enrichment region

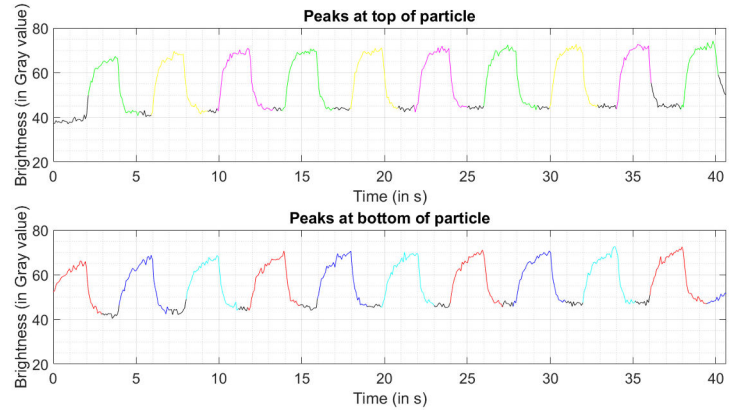


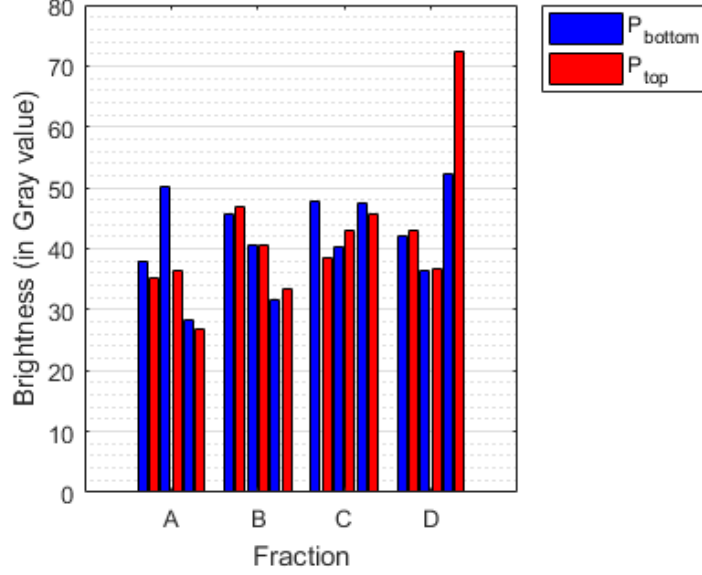
Figure 7: Separation of rows of peaks into regions containing 1 peak

3 Results & discussion

For the concentrations of $10 \mu\text{M}$ and 10 mM *KCl* clear polarization effects have been observed. At 20 mM *KCl* slight CP effects were observable, though it has to be noted that these chips are smaller in length than the chips of Figure 2, having a higher electric field in the measurements. The current through the chip increased to approximately 1 mA at this concentration. At 25 , 50 , 100 mM and 1 M *KCl* concentrations no ICP effects were observable. The region of ICP effects happening and non-ICP effects is between 10 and 20 mM *KCl*. Concentrations of 10 , 12.5 , 15 , 17.5 and 20 mM *KCl* were tested with particles inside of the chips of Figure 2. With these chips no ICP effects were observable at a concentration of 20 mM *KCl*, but were observable at 17.5 mM *KCl*. The ICP effects observable differed per chip, leading to inconsistencies in ICP between different particle densities, thus different effective nanopore sizes.

With the data analysis in *Matlab*, the bar graphs are plotted for the different concentrations of *KCl*, see Figures 8, 9, 10, 11 and 12.

Average of maximum peak values 10 mM KCl



Average of maximum peak values 15 mM KCl

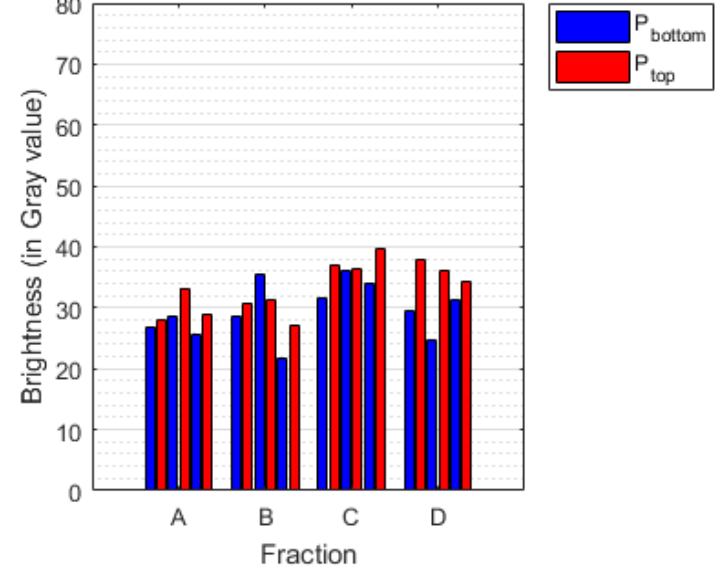
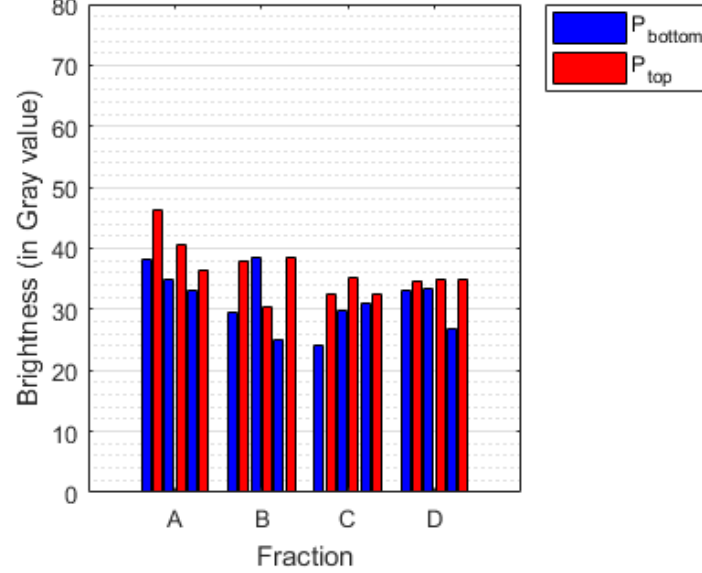


Figure 8: Results of polarization regions for 10 mM KCl

Figure 10: Results of polarization regions for 15 mM KCl

Average of maximum peak values 12.5 mM KCl



Average of maximum peak values 17.5 mM KCl

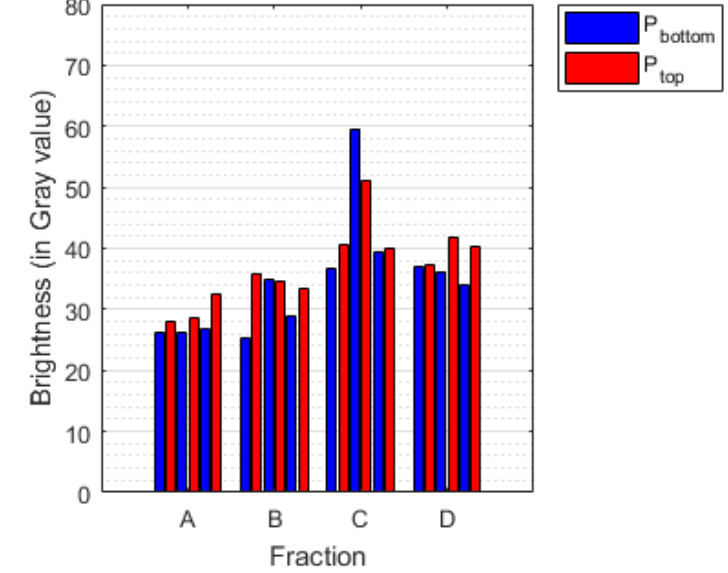


Figure 9: Results of polarization regions for 12.5 mM KCl

Figure 11: Results of polarization regions for 17.5 mM KCl

Average of maximum peak values 20 mM KCl

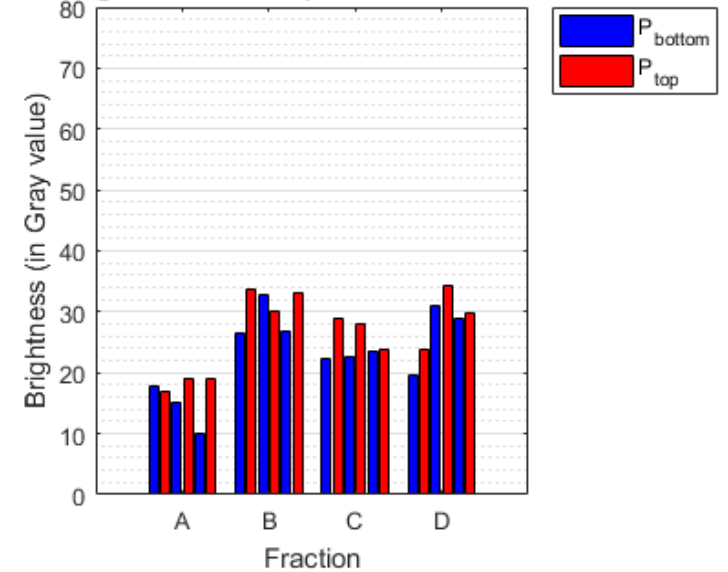


Figure 12: Results of polarization regions for 20 mM KCl

From Figures 8 up to and including 12 it can be seen that the time-average of the maximum brightness in each polarization region decreases for higher concentrations, indicating that ICP effects decrease for larger concentrations. This corresponds to the theory of ionic concentration polarization: the electrical double layers of the nanopores of the FCC particle get thinner for higher concentrations of KCl, decreasing the surface conductivity of the EDLs and making the bulk electrolyte conductivity more dominant in the equation for the Dukhin number. This theory is supported by the graph of Figure 13. In this graph, the Dukhin length, a number corresponding to the Dukhin number divided by the nanopore size, and the Debye length, a number proportional to the EDL thickness, are plotted versus the concentration of KCl. The Dukhin length decreases for higher concentrations, which is in correspondence with the previous shown results. If the Dukhin number would be constant for every concentration, the nanopore size that would be affected by ICP would be bigger for higher concentrations as the EDL is thinner, resulting in less ICP effects.

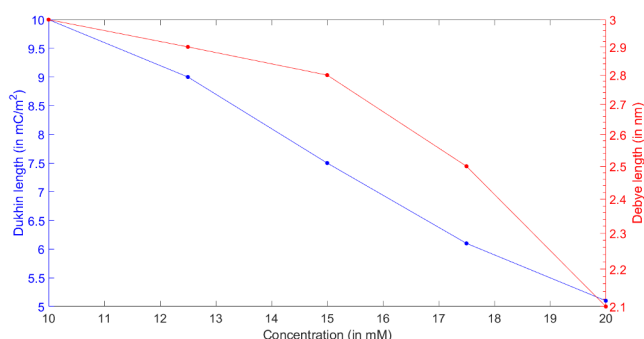


Figure 13: Calculated Dukhin length and Debye length versus concentration

Both the differences in polarization regions between top and bottom of the FCC particles and the differences in ICP between different particle densities, thus different nanopore sizes, are inconsistent. This inconsistency in ICP for the different nanopore sizes can be explained by the fact that FCC particles have a very heterogeneous pore structure: even though many nanopores might be partially blocked at higher densities, decreasing the effective nanopore size and thus increasing ICP, there are nanopores by which the overlap of EDLs will become too large, through which ICP cannot take place anymore. Also, nanopores with nanopore sizes that do not contribute in ICP in fresh state of FCC particles, can contribute to ICP when the pores are partially blocked, as the effective nanopore size is decreased. To have a proper measurement on the ICP effects for FCC particles with different densities, FCC particles with homogeneous pore sizes in fresh state should be taken, which in practice do not exist.

4 Conclusions & outlook

This research started with an introduction, in which theory about the structure of fluid catalytic cracking particles and theory about concentration polarization was discussed. This was followed by an experimental section in which restrictions were put on the measurement setup and chips to be used. These restrictions were the FCC particles to be stagnant,

having a stable pH, using the same conditions on the potentials, camera and amount of lighting in each measurement. PDMS chips were fabricated and bonded to glass plates after inserting the FCC particles in the microfluidic channels. ICP effects were first tested with KCl concentrations ranging from 10 μM to 1 M on which potentials of 100 V were applied. After the limit of concentration for ICP phenomena was known concentrations of 10, 12.5, 15, 17.5 and 20 mM KCl were measured and analyzed. The maximum brightness of the polarization regions of each particle over time were calculated. From this, the average was taken and plotted in a bar graph, being grouped per density fraction. It has been demonstrated that ICP effects of FCC particles get smaller for higher concentrations of KCl. Additionally, it has been shown that there are inconsistent differences in ICP effects between FCC particles of different densities. The latter phenomena is caused by the heterogeneous pore sizes within the FCC particle, as larger nanopores that are not affected by ICP in fresh state, might get affected when partially blocked by Fe, Ni or V, hence decreasing the effective nanopore sizes.

To show more consistent differences in ICP phenomena for FCC particles with different densities, thus different effective nanopore sizes, FCC particles should be chosen with an almost homogeneous distribution of nanopore sizes in fresh state. Unfortunately, these are not available in practice. Silica particles with homogeneous pore structures could be an alternative for this, however, these were not obtainable during this research. For future research, more measurements have to be done on the FCC particles with different KCl concentrations to have consistent data and to know the statistics. Next to this, the RC-time can be analyzed to know the steady-state behavior of polarization for the FCC particles.

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Appendices

Appendix A: Original chip designs

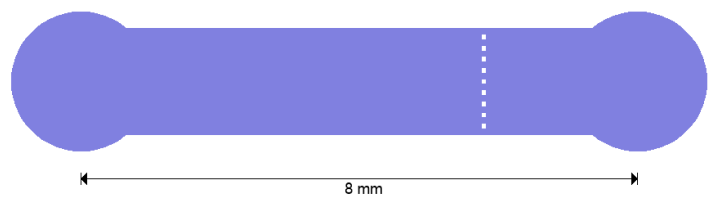


Figure 14: Chips that were used for the first measurements

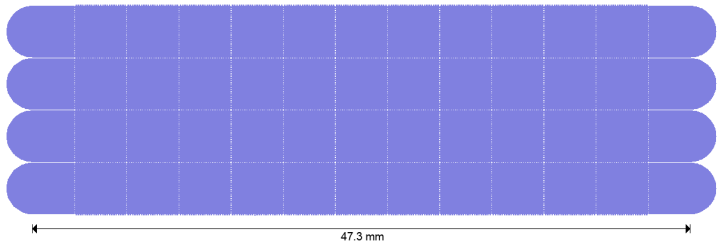


Figure 15: Chips that were originally planned to be used for the final measurements, unfortunately not all compartments within the chip could be filled with electrolyte solution.

Appendix B: Macro used for data retrieval in ImageJ

```
macro "Stack profile Data" {
    if (!(selectionType()==0 || selectionType==5 || selectionType==6))
        exit("Line or Rectangle Selection Required");
    setBatchMode(true);

    run("Plot Profile");
    Plot.getValues(x, y);
    run("Clear Results");
    for (i=0; i<x.length; i++)
        setResult("x", i, x[i]);
    close();

    n = nSlices;
    for (slice=1; slice<=n; slice++) {
        showProgress(slice, n);
        setSlice(slice);
        profile = getProfile();
        sliceLabel = toString(slice);
        sliceData = split(getMetadata("Label"), "\n");
        if (sliceData.length>0) {
            line0 = sliceData[0];
            if (lengthOf(sliceLabel) > 0)
                sliceLabel = sliceLabel + " (" + line0 + ")";
        }
        for (i=0; i<profile.length; i++)
            setResult(sliceLabel, i, profile[i]);
    }
    setBatchMode(false);
    updateResults;
}
```

Appendix C: Matlab script for data analysis

```
fps = 12.380; %Framerate in fps
t = linspace(0, length(F1B_6_P1)/fps, length(F1B_6_P1));
[m, n] = size(F1B_6_P1);
srfx = t;
srfy = [1: m];
n = [1: n];
surf(srfx, srfy, F1B_6_P1);

%%
part = F1B_6_P1(1:136, :);
part2 = F1B_6_P1(137:end, :);
background = F1B_6_P1(1:25, :);

Values = max(part);
Values2 = max(part2);
bckgnd_vals= max(max(background));

plot(Values, 'b')
hold on
plot(Values2, 'r')
xlim([0 max(n)])
xlabel('Time (in frames)')
ylabel('Brightness (in Gray value)')
hold off

%%
[zdep1, Largest_column] = max(Values);
[zdep2, Largest_column2] = max(Values2);
[zdep3, Largest_row] = max(part(:, Largest_column));
[zdep4, Largest_row2] = max(part2(:, Largest_column2));
peaks_Bottom = part(Largest_row, :);
peaks_Top = part2(Largest_row2, :);

figure, clf
subplot(2,1,1)
plot(t, peaks_Top, 'r')
hold on
%plot(t, peaks_Top, 'r')
xlim([0 max(t)])
ylim([20 80])
grid on
grid minor
xlabel('Time (in s)')
ylabel('Brightness (in Gray value)')
title('Peaks on top side particle')%, 'Peaks on top side particle',
'Location', 'bestoutside')
hold off
set(gca, 'fontsize', 20)

subplot(2,1,2)
plot(t, peaks_Bottom, 'b')
hold on
%plot(t, peaks_Top, 'r')
xlim([0 max(t)])
ylim([20 80])
grid on
```

```

grid minor
xlabel('Time (in s)')
ylabel('Brightness (in Gray value)')
title('Peaks on bottom side particle')%, 'Peaks on top side particle',
'Location', 'bestoutside')
hold off
set(gca, 'fontsize', 20)
%%
polarization_peaks = max(F1B_6_P1);
plot(t, polarization_peaks)
grid on
grid minor
%take_peaks = [t' polarization_peaks]';

%% Separate graph in different timeframes
%cutter = 2 * fps;
region_1 = peaks_Bottom(1:37);           %'r'
region_2 = peaks_Top(27:65);             %'g'
region_3 = peaks_Bottom(50:87);          %'b'
region_4 = peaks_Top(74:116);            %'y'
region_5 = peaks_Bottom(100:139);        %'c'
region_6 = peaks_Top(123:165);           %'m'
region_7 = peaks_Bottom(146:185);        %'r'
region_8 = peaks_Top(171:210);           %'g'
region_9 = peaks_Bottom(198:235);        %'b'
region_10 = peaks_Top(222:258);          %'y'
region_11 = peaks_Bottom(245:285);       %'c'
region_12 = peaks_Top(270:310);          %'m'
region_13 = peaks_Bottom(297:336);       %'r'
region_14 = peaks_Top(322:362);          %'g'
region_15 = peaks_Bottom(344:383);       %'b'
region_16 = peaks_Top(371:407);          %'y'
region_17 = peaks_Bottom(396:435);       %'c'
region_18 = peaks_Top(421:447);          %'m' CHanged = -->447
region_19 = peaks_Bottom(446:488);       %'r'
region_20 = peaks_Top(469:497);          %'g'
region_21 = peaks_Bottom(489:end);       %'b'

time_1 = t(1:37);           %'r'
time_2 = t(27:65);          %'g'
time_3 = t(50:87);          %'b'
time_4 = t(74:116);         %'y'
time_5 = t(100:139);        %'c'
time_6 = t(123:165);        %'m'
time_7 = t(146:185);        %'r'
time_8 = t(171:210);        %'g'
time_9 = t(198:235);        %'b'
time_10 = t(222:258);       %'y'
time_11 = t(245:285);       %'c'
time_12 = t(270:310);       %'m'
time_13 = t(297:336);       %'r'
time_14 = t(322:362);       %'g'
time_15 = t(344:383);       %'b'
time_16 = t(371:407);       %'y'
time_17 = t(396:435);       %'c'
time_18 = t(421:447);       %'m' Changed = --> 447
time_19 = t(446:488);       %'r'
time_20 = t(469:497);       %'g'
time_21 = t(489:end);       %'b'

figure; clf;

```

```

subplot(2,1,2)
plot(t, peaks_Bottom, 'k')
hold on
plot(time_1, region_1, 'r')
plot(time_3, region_3, 'b')
plot(time_5, region_5, 'c')
plot(time_7, region_7, 'r')
plot(time_9, region_9, 'b')
plot(time_11, region_11, 'c')
plot(time_13, region_13, 'r')
plot(time_15, region_15, 'b')
plot(time_17, region_17, 'c')
plot(time_19, region_19, 'r')
plot(time_21, region_21, 'b')
grid on
grid minor
xlabel('Time (in s)')
ylabel('Brightness (in Gray value)')
title('Peaks at bottom of particle')
xlim([0 max(t)])
ylim([20 80])
hold off
set(gca, 'fontsize', 20)
subplot(2,1,1)
plot(t, peaks_Top, 'k')
hold on
plot(time_2, region_2, 'g')
plot(time_4, region_4, 'y')
plot(time_6, region_6, 'm')
plot(time_8, region_8, 'g')
plot(time_10, region_10, 'y')
plot(time_12, region_12, 'm')
plot(time_14, region_14, 'g')
plot(time_16, region_16, 'y')
plot(time_18, region_18, 'm')
plot(time_20, region_20, 'g')
grid on
grid minor
xlabel('Time (in s)')
ylabel('Brightness (in Gray value)')
title('Peaks at top of particle')
xlim([0 max(t)])
ylim([20 80])
hold off
set(gca, 'fontsize', 20)
%%
%Determine peaks and its locations from each timeframe
[localp1, ip1] = max(region_1);
[localv1, iv1] = min(time_1);

[localp2, ip2] = max(region_2);
[localv2, iv2] = min(time_2);
ip2 = ip2 + iv2 - 1;

[localp3, ip3] = max(region_3);
[localv3, iv3] = min(time_3);
ip3 = ip3 + iv3 - 1;

[localp4, ip4] = max(region_4);
[localv4, iv4] = min(time_4);
ip4 = ip4 + iv4 - 1;

```

```

[localp5, ip5] = max(region_5);
[localv5, iv5] = min(time_5);
ip5 = ip5 + iv5 - 1;

[localp6, ip6] = max(region_6);
[localv6, iv6] = min(time_6);
ip6 = ip6 + iv6 - 1;

[localp7, ip7] = max(region_7);
[localv7, iv7] = min(time_7);
ip7 = ip7 + iv7 - 1;

[localp8, ip8] = max(region_8);
[localv8, iv8] = min(time_8);
ip8 = ip8 + iv8 - 1;

[localp9, ip9] = max(region_9);
[localv9, iv9] = min(time_9);
ip9 = ip9 + iv9 - 1;

[localp10, ip10] = max(region_10);
[localv10, iv10] = min(time_10);
ip10 = ip10 + iv10 - 1;

[localp11, ip11] = max(region_11);
[localv11, iv11] = min(time_11);
ip11 = ip11 + iv11 - 1;

[localp12, ip12] = max(region_12);
[localv12, iv12] = min(time_12);
ip12 = ip12 + iv12 - 1;

[localp13, ip13] = max(region_13);
[localv13, iv13] = min(time_13);
ip13 = ip13 + iv13 - 1;

[localp14, ip14] = max(region_14);
[localv14, iv14] = min(time_14);
ip14 = ip14 + iv14 - 1;

[localp15, ip15] = max(region_15);
[localv15, iv15] = min(time_15);
ip15 = ip15 + iv15 - 1;

[localp16, ip16] = max(region_16);
[localv16, iv16] = min(time_16);
ip16 = ip16 + iv16 - 1;

[localp17, ip17] = max(region_17);
[localv17, iv17] = min(time_17);
ip17 = ip17 + iv17 - 1;

[localp18, ip18] = max(region_18);
[localv18, iv18] = min(time_18);
ip18 = ip18 + iv18 - 1;

[localp19, ip19] = max(region_19);

```

```

[localv19, iv19] = min(time_19);
ip19 = ip19 + iv19 - 1;

[localp20, ip20] = max(region_20);
[localv20, iv20] = min(time_20);
ip20 = ip20 + iv20 - 1;

[localp21, ip21] = max(region_21);
ip21 = ip21 + iv20;

%%
local_peaks = [localp1 localp3 localp5 localp7 localp9 localp11 localp13
localp15 localp17 localp19];
local_peaks1 = [localp2 localp4 localp6 localp8 localp10 localp12 localp14
localp16 localp18 localp20];
avg_of_peaks_bottom = mean(local_peaks);
avg_of_peaks_top = mean(local_peaks1);

%% Histograms

% Chip 6, 10 mM

b_p_a_10_F1A_P1 = 63.5134;
t_p_a_10_F1A_P1 = 60.7468;
bck_10_F1A_P1 = 25.48101;

b_p_a_10_F1A_P2 = 75.3143;
t_p_a_10_F1A_P2 = 61.5500;
bck_10_F1A_P2 = 25.19444;

b_p_a_10_F1A_P3 = 53.2078;
t_p_a_10_F1A_P3 = 51.8307;
bck_10_F1A_P3 = 25.02353;

b_p_a_10_F1B_P1 = 70.1199;
t_p_a_10_F1B_P1 = 71.2934;
bck_10_F1B_P1 = 24.38416;

b_p_a_10_F1B_P2 = 65.8236;
t_p_a_10_F1B_P2 = 66.0471;
bck_10_F1B_P2 = 25.36842;

b_p_a_10_F1B_P3 = 56.0313;
t_p_a_10_F1B_P3 = 57.9126;
bck_10_F1B_P3 = 24.47863;

b_p_a_10_F2_P1 = 71.0000;
t_p_a_10_F2_P1 = 61.8889;
bck_10_F2_P1 = 23.28800;

b_p_a_10_F2_P2 = 65.4522;
t_p_a_10_F2_P2 = 67.8957;
bck_10_F2_P2 = 25.04865;

b_p_a_10_F2_P3 = 72.2917;
t_p_a_10_F2_P3 = 70.4251;
bck_10_F2_P3 = 24.79200;

```

```

b_p_a_10_F3_P1 = 73.3788;
t_p_a_10_F3_P1 = 74.3315;
bck_10_F3_P1 = 31.41176;

b_p_a_10_F3_P2 = 68.4625;
t_p_a_10_F3_P2 = 68.7500;
bck_10_F3_P2 = 32.03243;

b_p_a_10_F3_P3 = 84.9050;
t_p_a_10_F3_P3 = 104.8450;
bck_10_F3_P3 = 32.63399;

%% 17.5 mM

b_p_a_17_5_F1A_P1 = 50.1889;
t_p_a_17_5_F1A_P1 = 52.1555;
bck_17_5_F1A_P1 = 24.112068;

b_p_a_17_5_F1A_P2 = 50.2199;
t_p_a_17_5_F1A_P2 = 52.5000;
bck_17_5_F1A_P2 = 24.011906;

b_p_a_17_5_F1A_P3 = 50.3813;
t_p_a_17_5_F1A_P3 = 56.0998;
bck_17_5_F1A_P3 = 23.56044;

b_p_a_17_5_F1B_P1 = 49.1799;
t_p_a_17_5_F1B_P1 = 59.6599;
bck_17_5_F1B_P1 = 23.76744;

t_p_a_17_5_F1B_P2 = 58.6917;
b_p_a_17_5_F1B_P2 = 59.0999;
bck_17_5_F1B_P2 = 24.10588;

b_p_a_17_5_F1B_P3 = 52.4866;
t_p_a_17_5_F1B_P3 = 56.9999;
bck_17_5_F1B_P3 = 23.63025;

b_p_a_17_5_F2_P1 = 61.0550;
t_p_a_17_5_F2_P1 = 64.8800;
bck_17_5_F2_P1 = 24.376812;

b_p_a_17_5_F2_P2 = 84.3056;
t_p_a_17_5_F2_P2 = 75.8278;
bck_17_5_F2_P2 = 24.68067;

b_p_a_17_5_F2_P3 = 63.4067;
t_p_a_17_5_F2_P3 = 64.1533;
bck_17_5_F2_P3 = 24.07292;

b_p_a_17_5_F3_P1 = 63.7234;
t_p_a_17_5_F3_P1 = 64.2825;
bck_17_5_F3_P1 = 26.82979;

b_p_a_17_5_F3_P2 = 62.5265;
t_p_a_17_5_F3_P2 = 68.2104;
bck_17_5_F3_P2 = 26.317038;

```

```
b_p_a_17_5_F3_P3 = 59.5295;  
t_p_a_17_5_F3_P3 = 65.6352;  
bck_17_5_F3_P3 = 25.467289;
```

%% 15 mM

```
b_p_a_15_F1A_P1 = 49.7059;  
t_p_a_15_F1A_P1 = 50.8646;  
bck_15_F1A_P1 = 22.923077;
```

```
b_p_a_15_F1A_P2 = 52.1312;  
t_p_a_15_F1A_P2 = 56.7000;  
bck_15_F1A_P2 = 23.472221;
```

```
b_p_a_15_F1A_P3 = 48.7667;  
t_p_a_15_F1A_P3 = 51.9222;  
bck_15_F1A_P3 = 23.01869;
```

```
b_p_a_15_F1B_P1 = 52.0286;  
t_p_a_15_F1B_P1 = 54.1573;  
bck_15_F1B_P1 = 23.504587;
```

```
t_p_a_15_F1B_P2 = 55.2668;  
b_p_a_15_F1B_P2 = 59.4933;  
bck_15_F1B_P2 = 23.94521;
```

```
b_p_a_15_F1B_P3 = 45.2648;  
t_p_a_15_F1B_P3 = 50.5587;  
bck_15_F1B_P3 = 23.495798;
```

```
b_p_a_15_F2_P1 = 56.0389;  
t_p_a_15_F2_P1 = 61.6166;  
bck_15_F2_P1 = 24.534483;
```

```
b_p_a_15_F2_P2 = 60.7521;  
t_p_a_15_F2_P2 = 60.9738;  
bck_15_F2_P2 = 24.606060;
```

```
b_p_a_15_F2_P3 = 58.1563;  
t_p_a_15_F2_P3 = 63.8186;  
bck_15_F2_P3 = 24.19048;
```

```
b_p_a_15_F3_P1 = 54.5952;  
t_p_a_15_F3_P1 = 62.9287;  
bck_15_F3_P1 = 25.079645;
```

```
b_p_a_15_F3_P2 = 51.2313;  
t_p_a_15_F3_P2 = 62.6094;  
bck_15_F3_P2 = 26.46296;
```

```
b_p_a_15_F3_P3 = 55.7050;  
t_p_a_15_F3_P3 = 58.7850;  
bck_15_F3_P3 = 24.49412;
```

%% 12.5 mM

```
b_p_a_12_5_F1A_P1 = 65.6866 ;  
t_p_a_12_5_F1A_P1 = 73.7067;  
bck_12_5_F1A_P1 = 27.46428;
```

```

b_p_a_12_5_F1A_P2 = 62.8750;
t_p_a_12_5_F1A_P2 = 68.5688;
bck_12_5_F1A_P2 = 28.098902;

b_p_a_12_5_F1A_P3 = 62.0722;
t_p_a_12_5_F1A_P3 = 65.3612;
bck_12_5_F1A_P3 = 28.81707;

b_p_a_12_5_F1B_P1 = 52.7858;
t_p_a_12_5_F1B_P1 = 61.4071;
bck_12_5_F1B_P1 = 23.35484;

t_p_a_12_5_F1B_P2 = 53.9722;
b_p_a_12_5_F1B_P2 = 62.2667;
bck_12_5_F1B_P2 = 23.61667;

b_p_a_12_5_F1B_P3 = 49.9420;
t_p_a_12_5_F1B_P3 = 63.4262;
bck_12_5_F1B_P3 = 24.80583;

b_p_a_12_5_F2_P1 = 50.3131;
t_p_a_12_5_F2_P1 = 58.6522;
bck_12_5_F2_P1 = 26.19417;

b_p_a_12_5_F2_P2 = 56.4250;
t_p_a_12_5_F2_P2 = 61.9750;
bck_12_5_F2_P2 = 26.72549;

b_p_a_12_5_F2_P3 = 56.5001;
t_p_a_12_5_F2_P3 = 57.8000;
bck_12_5_F2_P3 = 25.40541;

b_p_a_12_5_F3_P1 = 59.6749;
t_p_a_12_5_F3_P1 = 61.2062;
bck_12_5_F3_P1 = 26.48913;

b_p_a_12_5_F3_P2 = 59.6293;
t_p_a_12_5_F3_P2 = 61.2236;
bck_12_5_F3_P2 = 26.221153;

b_p_a_12_5_F3_P3 = 52.6957;
t_p_a_12_5_F3_P3 = 60.7868;
bck_12_5_F3_P3 = 25.730770;

%% 20 mM

b_p_a_20_F1A_P1 = 48.7261;
t_p_a_20_F1A_P1 = 47.8518;
bck_20_F1A_P1 = 30.970150;

b_p_a_20_F1A_P2 = 43.9260;
t_p_a_20_F1A_P2 = 47.9778;
bck_20_F1A_P2 = 28.80556;

b_p_a_20_F1A_P3 = 38.7734;
t_p_a_20_F1A_P3 = 47.7335;
bck_20_F1A_P3 = 28.81373;

```

```

b_p_a_20_F1B_P1 = 51.0000;
t_p_a_20_F1B_P1 = 58.1642;
bck_20_F1B_P1 = 24.45098;

t_p_a_20_F1B_P2 = 54.7894;
b_p_a_20_F1B_P2 = 57.5527;
bck_20_F1B_P2 = 24.763889;

b_p_a_20_F1B_P3 = 50.7934;
t_p_a_20_F1B_P3 = 57.2468;
bck_20_F1B_P3 = 24.03030;

b_p_a_20_F2_P1 = 44.7668;
t_p_a_20_F2_P1 = 51.6000;
bck_20_F2_P1 = 22.53684;

b_p_a_20_F2_P2 = 44.9459;
t_p_a_20_F2_P2 = 50.3375;
bck_20_F2_P2 = 22.235294;

b_p_a_20_F2_P3 = 45.6584;
t_p_a_20_F2_P3 = 45.7167;
bck_20_F2_P3 = 22.01695;

b_p_a_20_F3_P1 = 43.7380;
t_p_a_20_F3_P1 = 47.8380;
bck_20_F3_P1 = 24.0950;

b_p_a_20_F3_P2 = 54.2922;
t_p_a_20_F3_P2 = 57.6538;
bck_20_F3_P2 = 23.26016;

b_p_a_20_F3_P3 = 51.0309;
t_p_a_20_F3_P3 = 51.8615;
bck_20_F3_P3 = 22.16058;

%%
%C = [2 2 3; 4 5 6; 4 6 7; 2 11 12];
C6_10mM_y = [b_p_a_10_F1A_P1 t_p_a_10_F1A_P1 b_p_a_10_F1A_P2
t_p_a_10_F1A_P2 b_p_a_10_F1A_P3 t_p_a_10_F1A_P3; b_p_a_10_F1B_P1
t_p_a_10_F1B_P1 b_p_a_10_F1B_P2 t_p_a_10_F1B_P2 b_p_a_10_F1B_P3
t_p_a_10_F1B_P3; b_p_a_10_F2_P1 t_p_a_10_F2_P1 b_p_a_10_F2_P2
t_p_a_10_F2_P2 b_p_a_10_F2_P3 t_p_a_10_F2_P3; b_p_a_10_F3_P1 t_p_a_10_F3_P1
b_p_a_10_F3_P2 t_p_a_10_F3_P2 b_p_a_10_F3_P3 t_p_a_10_F3_P3];
C6_10mM_x =
categorical({'A1_{bottom}', 'A1_{top}', 'A2_{bottom}', 'A2_{top}', 'A3_{bottom}'
, 'A3_{top}', 'B1_{bottom}', 'B1_{top}', 'B2_{bottom}', 'B2_{top}', 'B3_{bottom}'
, 'B3_{top}', 'C1_{bottom}', 'C1_{top}', 'C2_{bottom}', 'C2_{top}', 'C3_{bottom}'
, 'C3_{top}', 'D1_{bottom}', 'D1_{top}', 'D2_{bottom}', 'D2_{top}', 'D3_{bottom}'
, 'D3_{top}'}));

C6_12_5mM_y = [b_p_a_12_5_F1A_P1 t_p_a_12_5_F1A_P1 b_p_a_12_5_F1A_P2
t_p_a_12_5_F1A_P2 b_p_a_12_5_F1A_P3 t_p_a_12_5_F1A_P3; b_p_a_12_5_F1B_P1
t_p_a_12_5_F1B_P1 b_p_a_12_5_F1B_P2 t_p_a_12_5_F1B_P2 b_p_a_12_5_F1B_P3
t_p_a_12_5_F1B_P3; b_p_a_12_5_F2_P1 t_p_a_12_5_F2_P1 b_p_a_12_5_F2_P2
t_p_a_12_5_F2_P2 b_p_a_12_5_F2_P3 t_p_a_12_5_F2_P3; b_p_a_12_5_F3_P1
t_p_a_12_5_F3_P1 b_p_a_12_5_F3_P2 t_p_a_12_5_F3_P2 b_p_a_12_5_F3_P3
t_p_a_12_5_F3_P3];

```

```

C6_12_5mM_x =
categorical({'A1_{bottom}','A1_{top}','A2_{bottom}','A2_{top}','A3_{bottom}'
','A3_{top}','B1_{bottom}','B1_{top}','B2_{bottom}','B2_{top}','B3_{bottom}'
','B3_{top}','C1_{bottom}','C1_{top}','C2_{bottom}','C2_{top}','C3_{bottom}'
','C3_{top}','D1_{bottom}','D1_{top}','D2_{bottom}','D2_{top}','D3_{bottom}'
','D3_{top}'});

C6_15mM_y = [b_p_a_15_F1A_P1 t_p_a_15_F1A_P1 b_p_a_15_F1A_P2
t_p_a_15_F1A_P2 b_p_a_15_F1A_P3 t_p_a_15_F1A_P3; b_p_a_15_F1B_P1
t_p_a_15_F1B_P1 b_p_a_15_F1B_P2 t_p_a_15_F1B_P2 b_p_a_15_F1B_P3
t_p_a_15_F1B_P3; b_p_a_15_F2_P1 t_p_a_15_F2_P1 b_p_a_15_F2_P2
t_p_a_15_F2_P2 b_p_a_15_F2_P3 t_p_a_15_F2_P3; b_p_a_15_F3_P1 t_p_a_15_F3_P1
b_p_a_15_F3_P2 t_p_a_15_F3_P2 b_p_a_15_F3_P3 t_p_a_15_F3_P3];
C6_15mM_x =
categorical({'A1_{bottom}','A1_{top}','A2_{bottom}','A2_{top}','A3_{bottom}'
','A3_{top}','B1_{bottom}','B1_{top}','B2_{bottom}','B2_{top}','B3_{bottom}'
','B3_{top}','C1_{bottom}','C1_{top}','C2_{bottom}','C2_{top}','C3_{bottom}'
','C3_{top}','D1_{bottom}','D1_{top}','D2_{bottom}','D2_{top}','D3_{bottom}'
','D3_{top}'});

C6_17_5mM_y = [b_p_a_17_5_F1A_P1 t_p_a_17_5_F1A_P1 b_p_a_17_5_F1A_P2
t_p_a_17_5_F1A_P2 b_p_a_17_5_F1A_P3 t_p_a_17_5_F1A_P3; b_p_a_17_5_F1B_P1
t_p_a_17_5_F1B_P1 b_p_a_17_5_F1B_P2 t_p_a_17_5_F1B_P2 b_p_a_17_5_F1B_P3
t_p_a_17_5_F1B_P3; b_p_a_17_5_F2_P1 t_p_a_17_5_F2_P1 b_p_a_17_5_F2_P2
t_p_a_17_5_F2_P2 b_p_a_17_5_F2_P3 t_p_a_17_5_F2_P3; b_p_a_17_5_F3_P1
t_p_a_17_5_F3_P1 b_p_a_17_5_F3_P2 t_p_a_17_5_F3_P2 b_p_a_17_5_F3_P3
t_p_a_17_5_F3_P3];
C6_17_5mM_x =
categorical({'A1_{bottom}','A1_{top}','A2_{bottom}','A2_{top}','A3_{bottom}'
','A3_{top}','B1_{bottom}','B1_{top}','B2_{bottom}','B2_{top}','B3_{bottom}'
','B3_{top}','C1_{bottom}','C1_{top}','C2_{bottom}','C2_{top}','C3_{bottom}'
','C3_{top}','D1_{bottom}','D1_{top}','D2_{bottom}','D2_{top}','D3_{bottom}'
','D3_{top}'});

C6_20mM_y = [b_p_a_20_F1A_P1 t_p_a_20_F1A_P1 b_p_a_20_F1A_P2
t_p_a_20_F1A_P2 b_p_a_20_F1A_P3 t_p_a_20_F1A_P3; b_p_a_20_F1B_P1
t_p_a_20_F1B_P1 b_p_a_20_F1B_P2 t_p_a_20_F1B_P2 b_p_a_20_F1B_P3
t_p_a_20_F1B_P3; b_p_a_20_F2_P1 t_p_a_20_F2_P1 b_p_a_20_F2_P2
t_p_a_20_F2_P2 b_p_a_20_F2_P3 t_p_a_20_F2_P3; b_p_a_20_F3_P1 t_p_a_20_F3_P1
b_p_a_20_F3_P2 t_p_a_20_F3_P2 b_p_a_20_F3_P3 t_p_a_20_F3_P3];
C6_20mM_x =
categorical({'A1_{bottom}','A1_{top}','A2_{bottom}','A2_{top}','A3_{bottom}'
','A3_{top}','B1_{bottom}','B1_{top}','B2_{bottom}','B2_{top}','B3_{bottom}'
','B3_{top}','C1_{bottom}','C1_{top}','C2_{bottom}','C2_{top}','C3_{bottom}'
','C3_{top}','D1_{bottom}','D1_{top}','D2_{bottom}','D2_{top}','D3_{bottom}'
','D3_{top}'});

k = bckgnd_vals * ones(1, 6);
kx = [0:5];

bck_10mM = [bck_10_F1A_P1 bck_10_F1A_P1 bck_10_F1A_P2 bck_10_F1A_P2
bck_10_F1A_P3 bck_10_F1A_P3; bck_10_F1B_P1 bck_10_F1B_P1 bck_10_F1B_P2
bck_10_F1B_P2 bck_10_F1B_P3 bck_10_F1B_P3; bck_10_F2_P1 bck_10_F2_P1
bck_10_F2_P2 bck_10_F2_P2 bck_10_F2_P3 bck_10_F2_P3; bck_10_F3_P1
bck_10_F3_P1 bck_10_F3_P2 bck_10_F3_P2 bck_10_F3_P3 bck_10_F3_P3];
bck_12_5mM = [bck_12_5_F1A_P1 bck_12_5_F1A_P1 bck_12_5_F1A_P2
bck_12_5_F1A_P2 bck_12_5_F1A_P3 bck_12_5_F1A_P3; bck_12_5_F1B_P1
bck_12_5_F1B_P1 bck_12_5_F1B_P2 bck_12_5_F1B_P2 bck_12_5_F1B_P3
bck_12_5_F1B_P3; bck_12_5_F2_P1 bck_12_5_F2_P1 bck_12_5_F2_P2
bck_12_5_F2_P2 bck_12_5_F2_P3 bck_12_5_F2_P3; bck_12_5_F3_P1 bck_12_5_F3_P1
bck_12_5_F3_P2 bck_12_5_F3_P2 bck_12_5_F3_P3 bck_12_5_F3_P3];

```

```

bck_12_5_F3_P2 bck_12_5_F3_P2 bck_12_5_F3_P3 bck_12_5_F3_P3];
bck_15mM = [bck_15_F1A_P1 bck_15_F1A_P1 bck_15_F1A_P2 bck_15_F1A_P2
bck_15_F1A_P3 bck_15_F1A_P3; bck_15_F1B_P1 bck_15_F1B_P1 bck_15_F1B_P2
bck_15_F1B_P2 bck_15_F1B_P3 bck_15_F1B_P3; bck_15_F2_P1 bck_15_F2_P1
bck_15_F2_P2 bck_15_F2_P2 bck_15_F2_P3 bck_15_F2_P3; bck_15_F3_P1
bck_15_F3_P1 bck_15_F3_P2 bck_15_F3_P2 bck_15_F3_P3 bck_15_F3_P3];
bck_17_5mM = [bck_17_5_F1A_P1 bck_17_5_F1A_P1 bck_17_5_F1A_P2
bck_17_5_F1A_P2 bck_17_5_F1A_P3 bck_17_5_F1A_P3; bck_17_5_F1B_P1
bck_17_5_F1B_P1 bck_17_5_F1B_P2 bck_17_5_F1B_P2 bck_17_5_F1B_P3
bck_17_5_F1B_P3; bck_17_5_F2_P1 bck_17_5_F2_P1 bck_17_5_F2_P2
bck_17_5_F2_P2 bck_17_5_F2_P3 bck_17_5_F2_P3; bck_17_5_F3_P1 bck_17_5_F3_P1
bck_17_5_F3_P2 bck_17_5_F3_P2 bck_17_5_F3_P3 bck_17_5_F3_P3];
bck_20mM = [bck_20_F1A_P1 bck_20_F1A_P1 bck_20_F1A_P2 bck_20_F1A_P2
bck_20_F1A_P3 bck_20_F1A_P3; bck_20_F1B_P1 bck_20_F1B_P1 bck_20_F1B_P2
bck_20_F1B_P2 bck_20_F1B_P3 bck_20_F1B_P3; bck_20_F2_P1 bck_20_F2_P1
bck_20_F2_P2 bck_20_F2_P2 bck_20_F2_P3 bck_20_F2_P3; bck_20_F3_P1
bck_20_F3_P1 bck_20_F3_P2 bck_20_F3_P2 bck_20_F3_P3 bck_20_F3_P3];
x_any_mM = [0 0.875 0.875 1.125 1.125 1.5 1.5 1.875 1.875 2.125 2.125 2.5
2.5 2.875 2.875 3.125 3.125 3.5 3.5 3.875 3.875 4.125 4.125 5];

%%
y_10mM = C6_10mM_y - bck_10mM;
y_12_5mM = C6_12_5mM_y - bck_12_5mM;
y_15mM = C6_15mM_y - bck_15mM;
y_17_5mM = C6_17_5mM_y - bck_17_5mM;
y_20mM = C6_20mM_y - bck_20mM;

%y_p1 = y_10mM(1,:);

%%
% 10 mM KCl
cat = {'A','B','C','D'};
figure; clf;
subplot(2,3,1)
B_10 = bar(y_10mM);
B_10(1).FaceColor = 'blue';
B_10(2).FaceColor = 'red';
B_10(3).FaceColor = 'blue';
B_10(4).FaceColor = 'red';
B_10(5).FaceColor = 'blue';
B_10(6).FaceColor = 'red';
hold on
% bar(y_10mM(2,:))
% bar(y_10mM(3,:))
% bar(y_10mM(4,:))
%plot(x_any_mM, bck_10mM, 'r')
hold off
xticklabels(cat)
xticks(1:1:length(cat))
xtickangle(0)
legend('P_{bottom}', 'P_{top}', 'Location', 'bestoutside')
%legend('P1_{bottom}', 'P1_{top}', 'P2_{bottom}', 'P2_{top}',
'P3_{bottom}', 'P3_{top}', 'Background brightness', 'Location',
'bestoutside')
title('Average of maximum peak values 10 mM KCl')
xlabel('Fraction')
ylabel('Brightness (in Gray value)')
ax = gca;
ax.XGrid = 'off';

```

```

ax.YGrid = 'on';
ax.YMinorGrid = 'on';
xlim([0 5])
ylim([0 80])
%set(gca,'fontsize',14)

% 12.5 mM KCl
subplot(2,3,2)
B_12_5 = bar(y_12_5mM);
B_12_5(1).FaceColor = 'blue';
B_12_5(2).FaceColor = 'red';
B_12_5(3).FaceColor = 'blue';
B_12_5(4).FaceColor = 'red';
B_12_5(5).FaceColor = 'blue';
B_12_5(6).FaceColor = 'red';
hold on
%plot(x_any_mM, bck_12_5mM, 'r')
hold off
xticklabels(cat)
xticks(1:1:length(cat))
xtickangle(0)
legend('P_{bottom}', 'P_{top}', 'Location', 'bestoutside')
%legend('P1_{bottom}', 'P1_{top}', 'P2_{bottom}', 'P2_{top}',
'P3_{bottom}', 'P3_{top}', 'Background brightness', 'Location',
'bestoutside')
title('Average of maximum peak values 12.5 mM KCl')
xlabel('Fraction')
ylabel('Brightness (in Gray value)')
ax = gca;
ax.XGrid = 'off';
ax.YGrid = 'on';
ax.YMinorGrid = 'on';
xlim([0 5])
ylim([0 80])
%set(gca,'fontsize',14)

% 15 mM KCl
subplot(2,3,3)
B_15 = bar(y_15mM);
B_15(1).FaceColor = 'blue';
B_15(2).FaceColor = 'red';
B_15(3).FaceColor = 'blue';
B_15(4).FaceColor = 'red';
B_15(5).FaceColor = 'blue';
B_15(6).FaceColor = 'red';
hold on
%plot(x_any_mM, bck_15mM, 'r')
hold off
xticklabels(cat)
xticks(1:1:length(cat))
xtickangle(0)
legend('P_{bottom}', 'P_{top}', 'Location', 'bestoutside')
%legend('P1_{bottom}', 'P1_{top}', 'P2_{bottom}', 'P2_{top}',
'P3_{bottom}', 'P3_{top}', 'Background brightness', 'Location',
'bestoutside')
title('Average of maximum peak values 15 mM KCl')
xlabel('Fraction')
ylabel('Brightness (in Gray value)')
ax = gca;
ax.XGrid = 'off';
ax.YGrid = 'on';

```

```

ax.YMinorGrid = 'on';
xlim([0 5])
ylim([0 80])
%set(gca,'fontsize',14)

% 17.5 mM KCl
subplot(2,3,4)
B_17_5 = bar(y_17_5mM);
B_17_5(1).FaceColor = 'blue';
B_17_5(2).FaceColor = 'red';
B_17_5(3).FaceColor = 'blue';
B_17_5(4).FaceColor = 'red';
B_17_5(5).FaceColor = 'blue';
B_17_5(6).FaceColor = 'red';
hold on
%plot(x_any_mM, bck_17_5mM, 'r')
hold off
xticklabels(cat)
xticks(1:1:length(cat))
xtickangle(0)
legend('P_{bottom}', 'P_{top}', 'Location', 'bestoutside')
%legend('P1_{bottom}', 'P1_{top}', 'P2_{bottom}', 'P2_{top}',
'P3_{bottom}', 'P3_{top}', 'Background brightness', 'Location',
'bestoutside')
title('Average of maximum peak values 17.5 mM KCl')
xlabel('Fraction')
ylabel('Brightness (in Gray value)')
ax = gca;
ax.XGrid = 'off';
ax.YGrid = 'on';
ax.YMinorGrid = 'on';
xlim([0 5])
ylim([0 80])
%set(gca,'fontsize',14)

% 20 mM KCl
subplot(2,3,5)
B_20 = bar(y_20mM);
B_20(1).FaceColor = 'blue';
B_20(2).FaceColor = 'red';
B_20(3).FaceColor = 'blue';
B_20(4).FaceColor = 'red';
B_20(5).FaceColor = 'blue';
B_20(6).FaceColor = 'red';
hold on
%plot(x_any_mM, bck_20mM, 'r')
hold off
xticklabels(cat)
xticks(1:1:length(cat))
xtickangle(0)
legend('P_{bottom}', 'P_{top}', 'Location', 'bestoutside')
xlabel('Fraction')
ylabel('Brightness (in Gray value)')
ax = gca;
ax.XGrid = 'off';
ax.YGrid = 'on';
ax.YMinorGrid = 'on';
ylim([0 80])
%legend('P1_{bottom}', 'P1_{top}', 'P2_{bottom}', 'P2_{top}',
'P3_{bottom}', 'P3_{top}', 'Background brightness', 'Location',
'bestoutside');

```

```

title('Average of maximum peak values 20 mM KCl');
xlim([0 5])
ylim([0 80]);
%set(gca,'fontsize',14)

%% Nanopore size range from Dukhin number
%% 10 mM
F = 96485.33290;          % C/mol
z = 1;                    % valency
c0 = 10/1000;             % mM
sigma = 4e-6;             % (Ohm m)^-1
D = 0.25;
dukhin_approx1 = 10;      % Dukhin number approximation
G_bulk = 0.1278;          % (Ohm m)^-1
%G_sigma = 1;            % (Ohm m)^-1
%h_10mM = D/dukhin_approx;
h_10mM = (D * F * z * c0)/sigma;
E0 = 8.854187817e-12;
Er = 4.8;
R = 8.3144598;
T = 293;
lambda_D = sqrt((E0*Er*R*T)/((F^2)*c0));
lambda_D_squared = E0*Er*R*T/((F^2)*c0);
h_l_10mM = h_10mM / lambda_D;
lambda_D1 = 3;
%% 12.5 mM
F = 96485.33290;          % C/mol
z = 1;                    % valency
c0 = 12.5/1000;           % mM
sigma = 4e-6;             % (Ohm m)^-1
D = 0.25;
dukhin_approx2 = 9;       % Dukhin number approximation
%G_bulk = 1;              % (Ohm m)^-1
%G_sigma = 1;            % (Ohm m)^-1
%h_12_5mM = D/dukhin_approx;
h_12_5mM = (D * F * z * c0)/sigma;
E0 = 8.854187817e-12;
Er = 4.8;
R = 8.3144598;
T = 293;
lambda_D2 = 2.9;

h_l_12_5mM = h_12_5mM / lambda_D;
%% 15 mM
F = 96485.33290;          % C/mol
z = 1;                    % valency
c0 = 15/1000;             % mM
sigma = 4e-6;             % (Ohm m)^-1
D = 0.25;
dukhin_approx3 = 7.5;     % Dukhin number approximation
%G_bulk = 1;              % (Ohm m)^-1
%G_sigma = 1;            % (Ohm m)^-1
%h_15mM = D/dukhin_approx;
h_15mM = (D * F * z * c0)/sigma;
E0 = 8.854187817e-12;
Er = 4.8;
R = 8.3144598;
T = 293;
lambda_D3 = 2.8;

h_l_15mM = h_15mM / lambda_D;

```

```

%% 17.5 mM
F = 96485.33290;          % C/mol
z = 1;                    % valency
c0 = 17.5/1000;           % mM
sigma = 4e-6;             % (Ohm cm)^-1
D = 0.25;
dukhin_approx4 = 6.1;     % Dukhin number approximation
%G_bulk = 1;              % (Ohm m)^-1
%G_sigma = 1;             % (Ohm m)^-1
%h_17_5mM = D/dukhin_approx;
h_17_5mM = (D * F * z * c0)/sigma;
E0 = 8.854187817e-12;
Er = 4.8;
R = 8.3144598;
T = 293;
lambda_D4 = 2.5;

h_l_17_5mM = h_17_5mM / lambda_D;
%% 20 mM
F = 96485.33290;          % C/mol
z = 1;                    % valency
c0 = 20/1000;             % mM
sigma = 4e-6;             % (Ohm cm)^-1
D = 0.25;
dukhin_approx5 = 5.1;     % Dukhin number approximation
G_bulk = 0.2501;          % (Ohm m)^-1
%G_sigma = 1;             % (Ohm m)^-1
%h_20mM = D/dukhin_approx;
h_20mM = (D * F * z * c0)/sigma;
E0 = 8.854187817e-12;
Er = 4.8;
R = 8.3144598;
T = 293;
lambda_D5 = 2.1;

h_l_20mM = h_20mM/lambda_D;

%%
pore_size = [dukhin_approx1 dukhin_approx2 dukhin_approx3 dukhin_approx4
dukhin_approx5]';
pore_ratio = [lambda_D1 lambda_D2 lambda_D3 lambda_D4 lambda_D5]';
label = {'h_{10mM}', 'h_{12.5mM}', 'h_{15mM}', 'h_{17.5mM}', 'h_{20mM}'};
figure; clf;
set(figure,'defaultAxesColorOrder',[0 0 1]; [1 0 0]);
%bar(pore_size)
%xticklabels(label)
%xticks(1:1:length(label))
%xtickangle(0)
yyaxis left
plot([10 12.5 15 17.5 20]', pore_size, '-ob','MarkerFaceColor','b')
xlabel('Concentration (in mM)')
ylabel('Dukhin length (in mC/m^2)')
set(gca,'fontsize',20)
yyaxis right
semilogy([10 12.5 15 17.5 20]', pore_ratio, '-or','MarkerFaceColor','r')
ylabel('Debye length (in nm)')
set(gca,'fontsize',20)
%axis ij

```