Research Summary

Two-Phase Flow Experiments in Microfluidic Models and Numerical Simulation

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Outline

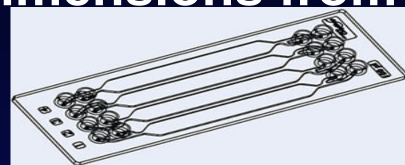
Methodologies	Microfluidic Devices & Pore-scale LBM	Control Volume Finite Difference Reservoir Simulation in Macro-scale	Multi-scale Approach	Parameters of Reservoir Simulation	Results	Future Work	Conclusions

Methodologies

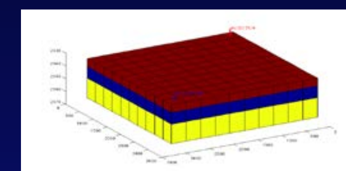
- IOR in oil reservoirs needs more understanding of the actual events inside pores. In this study, we would like to visualize IOR in porous media and simulate the observed process using a Control Volume Finite Difference reservoir simulation model.

Methodologies

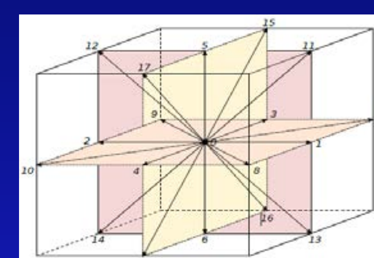
- Microfluidics is a practice of manipulating and controlling fluids in channels with dimensions from tens to hundreds of micrometers.



- Reservoir simulation is an important macro-scale tool of reservoir engineering in which computer models are used to predict flow of oil, water, and gas through porous media.



- Lattice Boltzmann method (LBM) is a class of computational fluid dynamics methods for direct simulation of fluid flow. The discrete Boltzmann equation with collision is solved to simulate the flow of Newtonian fluids at the pore scale.



Videos of water flooding/Microfluidic chips

https://www.youtube.com/watch?v=fC2bx3TfX8Y

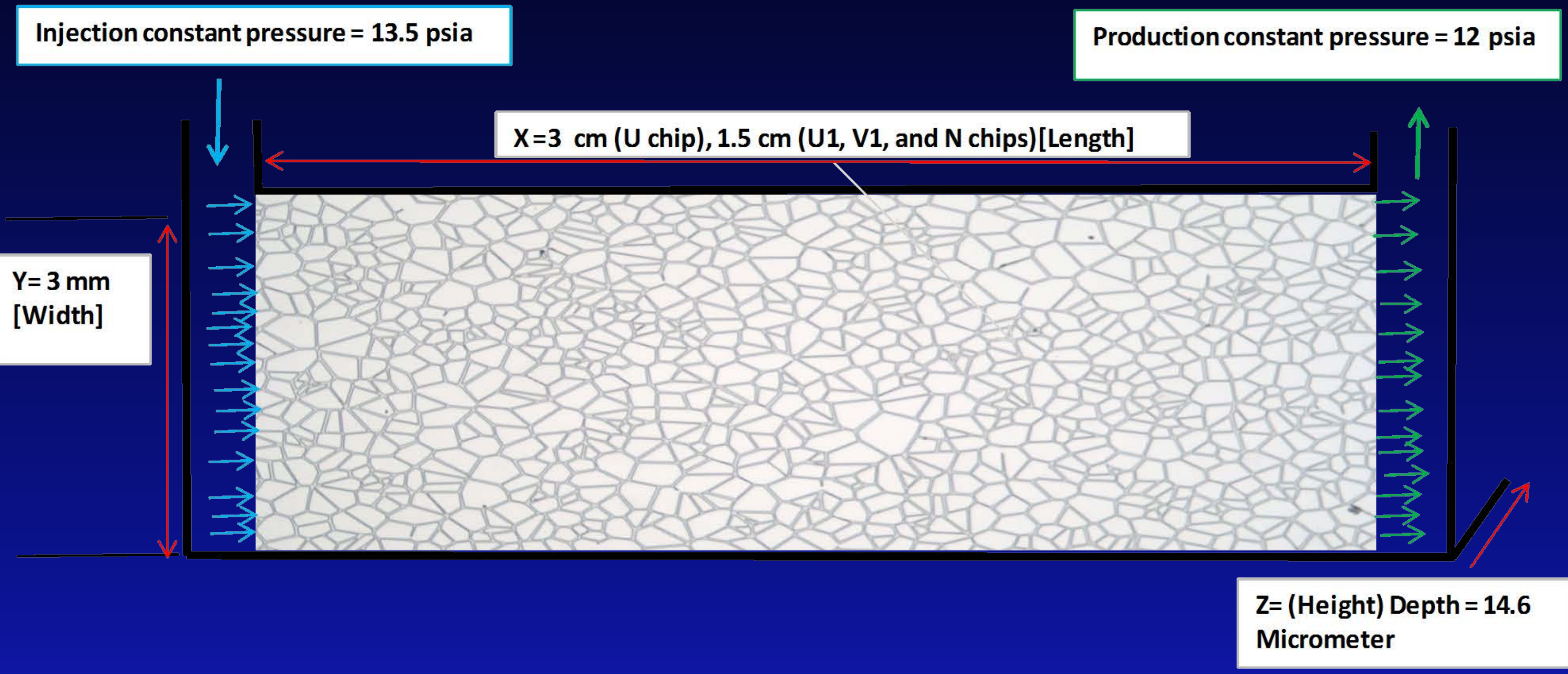
https://www.youtube.com/watch?v=9KOrXzuyvLE

Reference:

Xu, W., Ok, J. T., Xiao, F., Neeves, K. B. and Yin, X. 2014. Effect of Pore Geometry and Interfacial Tension on Water-Oil Displacement Efficiency in Oil-Wet Microfluidic Porous Media Analogs. Physics of Fluids, 26. doi:10.1039/c1lc20838a

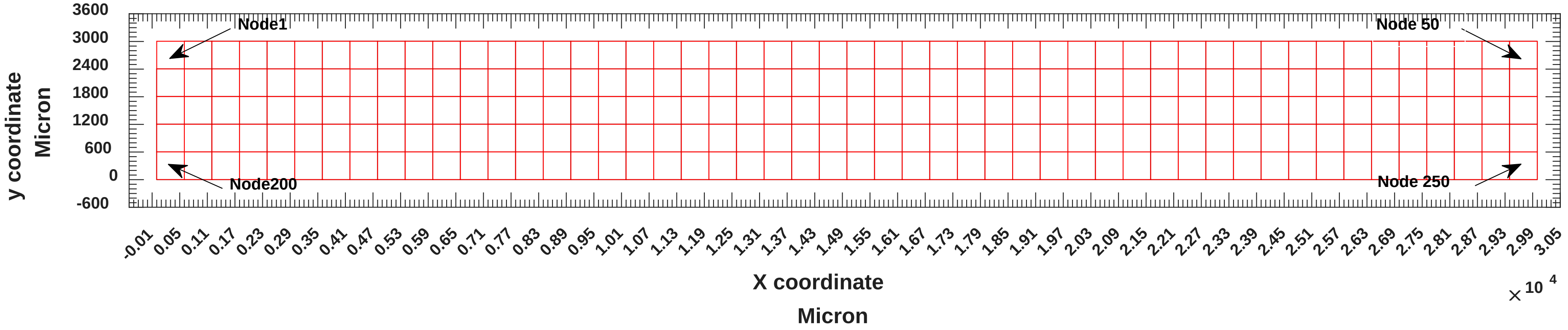
Microfluidic Devices & Pore-scale LBM

Geometry of microfluidic reservoir



Microfluidic Devices & Pore-scale LBM

Grid for reservoir simulation (U-chip)

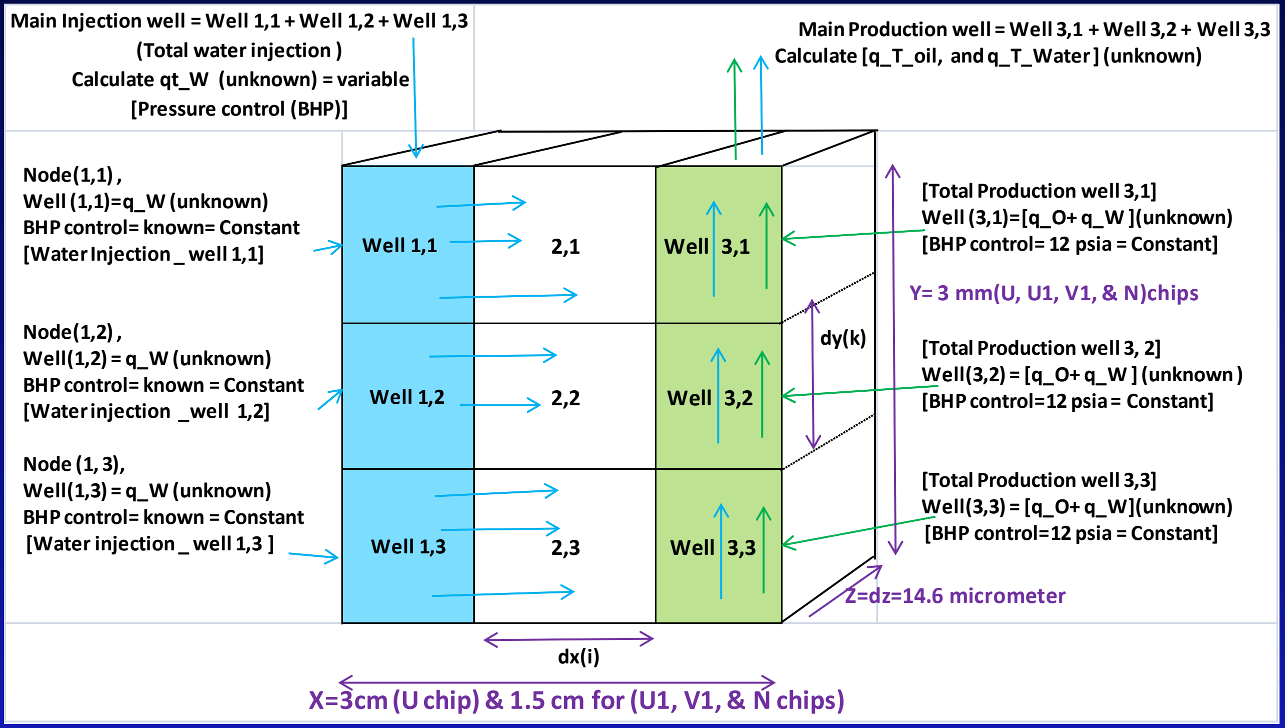


Microfluidic Devices & Pore-scale LBM

Porosity of each grid was obtained from geometry while permeability of each grid was obtained from the 3D LBM.

Control Volume Finite Difference Reservoir Simulation in Macro-scale

Typical 2D 3x3x1 grid nodes for W-O systems, constant BHP in the simulation code for U, U1, V1, and N chip's dimensions). In the real simulation, we have 5 injection wells & 5 production wells(50x5x1=250 nodes-U chip & 25x5x1=125 nodes-U1,V1 &N chips) dx=dy=600 microns & dz=14.6 microns, dt =0.01 sec. Also, Derived the new Darcy's law & source term conversion factor (6804.6)



Multi-scale approach

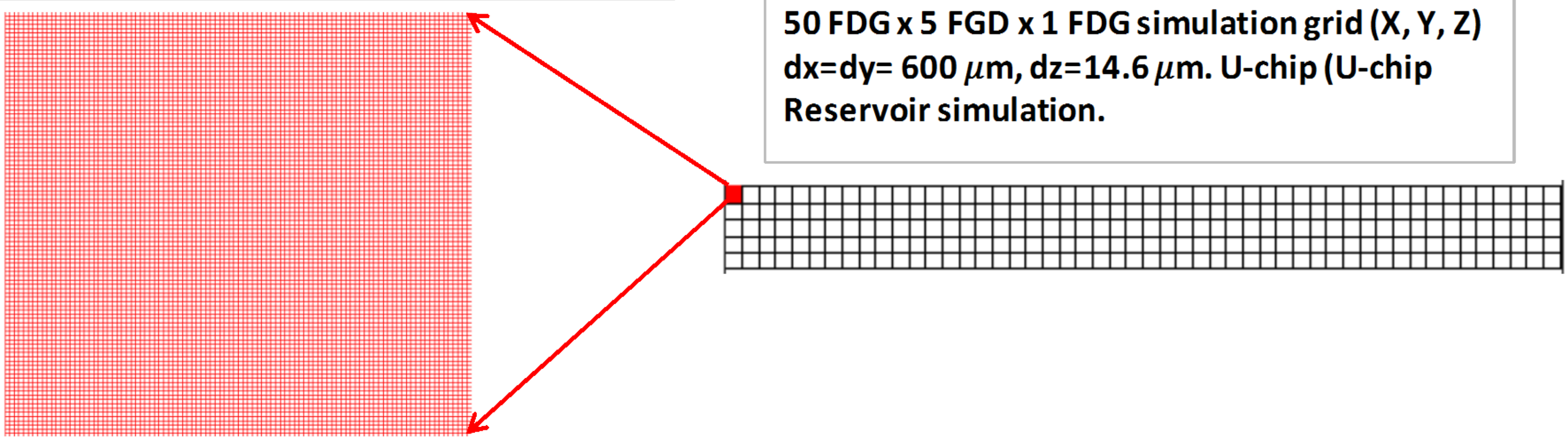
Macro and pore scales in this study.

Pore scale
[Lattice Boltsmann Method, 3D]
[600 μm x 600μm x 15μm]

(600 μm)x (600 μm) x (15 μm) = 5,400,000 Lattice
(Each 1 FDG has 5,400,000 LB Lattice)

Macro scale
[Finite Difference Grid (FDG)]
[3cm x 3mm x 14.6μm]-U chip
[1.5cm x 3mm x 14.6μm]-U1, V1, & N chips

50 FDG x 5 FGD x 1 FDG simulation grid (X, Y, Z)
dx=dy= 600 μm, dz=14.6 μm. U-chip (U-chip
Reservoir simulation.



Parameters of reservoir simulation

The results of the previously published microfluidic experimental work (U-chip).

1- From the lab Swr =0.055, Sor=0.05, chips dimensions (30000x3000x14.6 microns), oil & water viscosity= 42.46 cP & 0.94 cP.

2- Constant injection pressure = 13.5 psia, production pressure= 12 psia.

3- Capillary pressure curve (constant number (- 0.7 psi)) Will explain later.

4- RF=0.853 at BT=2840 sec (Avg. oil RF from several U chip experiments).

From the pore scale:

5- 250 porosity values (code).

6- 250 absolute permeability values (X permeability). Each permeability result takes 3-4 hours to get).

Other reservoir simulation parameters;

7- Cf = 3e-6 (1/psi), Co = 1e-5 (1/psi), Cw = 4e-6 (1/psi).

Parameters of reservoir simulation

Relative permeability & capillary pressure curves:

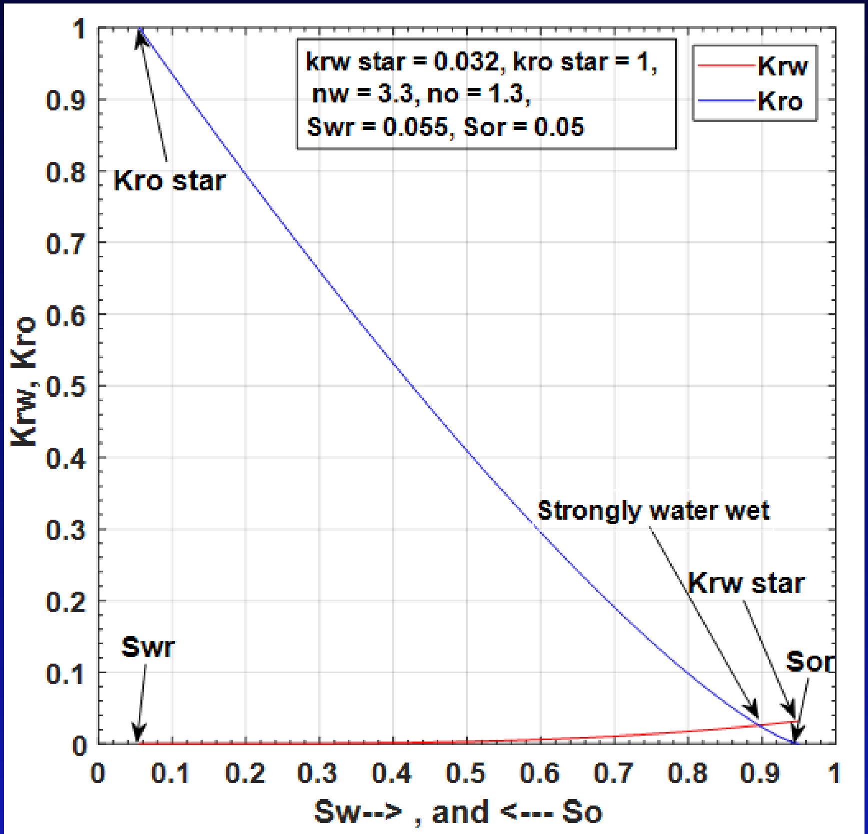
1-There is no known method to measure the endpoint Kro and Krw and saturation indices no and nw in microfluidic chips. In this study, we estimated the endpoints and saturation indices by matching the reservoir simulation to the lab measured RF value.

2- The capillary pressure value is a constant and equal to - 0.7 psia because the channel width (U chip) is 6 microns, and the chip is hydrophobic. However, for simulation, we need a curvature in the Pc curve, thus, we used the Brooks and Corey correlation. The water-oil capillary function is:

$$p_{c,wo} = p_o - p_w$$

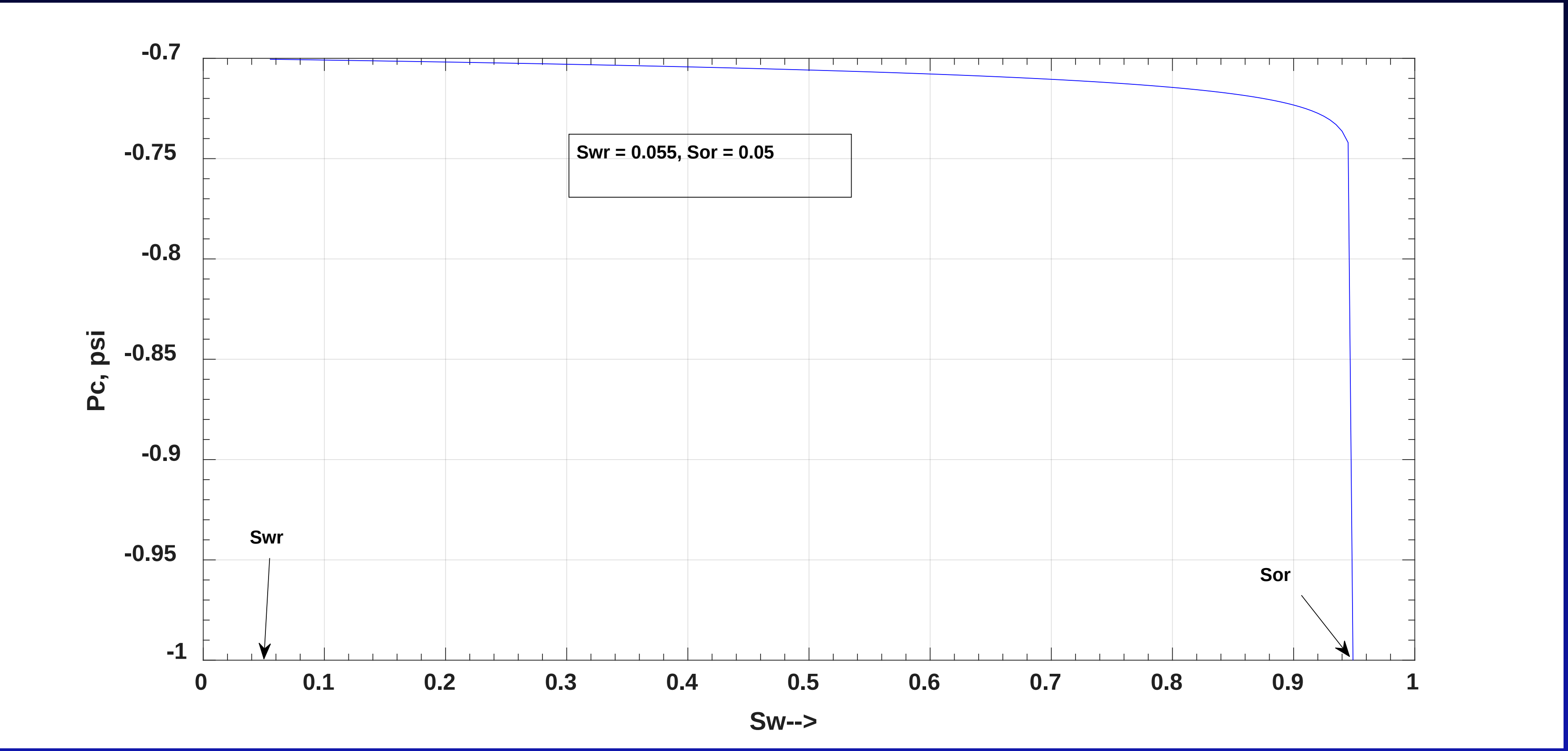
Parameters of reservoir simulation

Relative permeability curves used in matching the experiment oil recovery performance. The published measured water contact angle glass coated with SILANE is 110.7, and 110.9 with the PDMS; thus, slightly oil-wet.



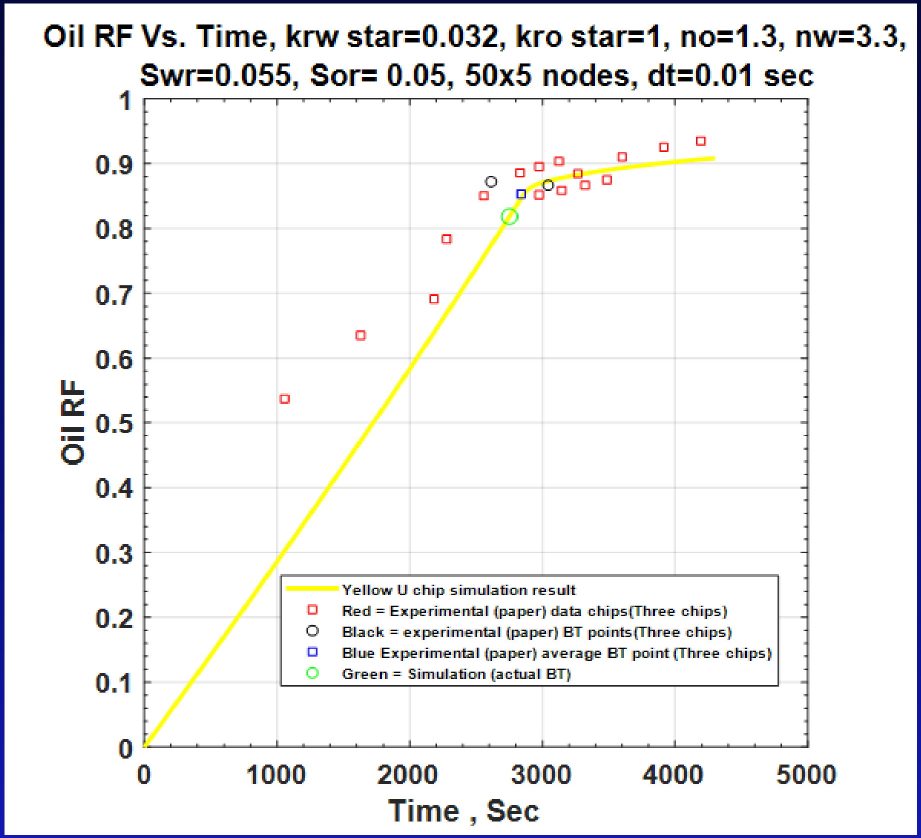
Parameters of reservoir simulation

Capillary pressure curve (Brooks and Corey correlation) that is best fit of the Pc= - 0.7 psi constant (U chip). $p_{c,wo} = p_o - p_w$



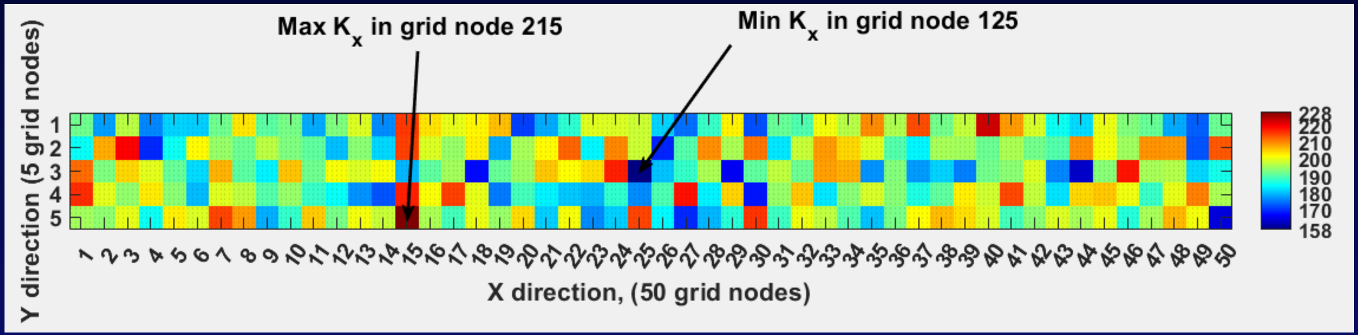
Results

Reservoir simulation results are very similar with the experimental results up to breakthrough time within 96% accuracy in oil recovery. This was achieved after adjusting the relative permeability curves.

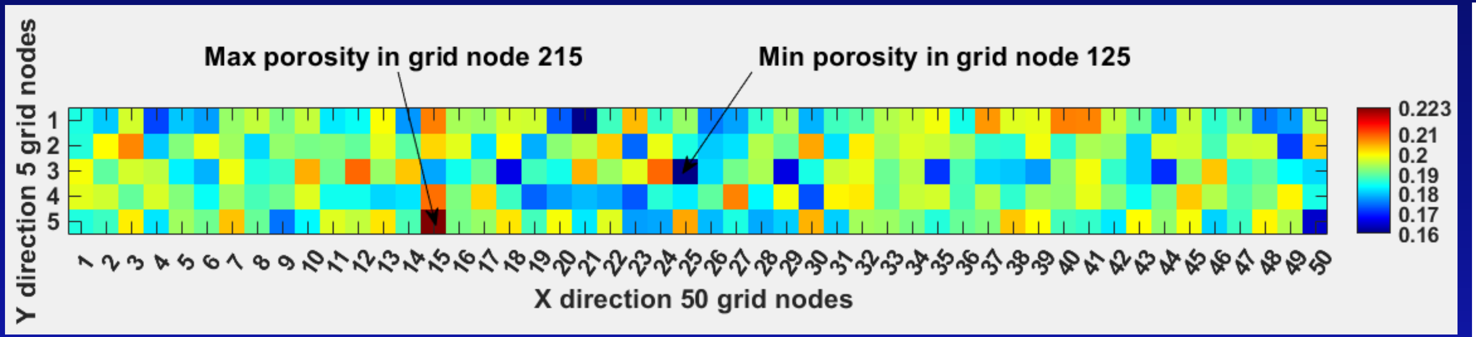


Additional results

- **Distribution of permeability & porosity**



Avg=194.02 mD
Max= 228.87 mD
Min=157.70 mD

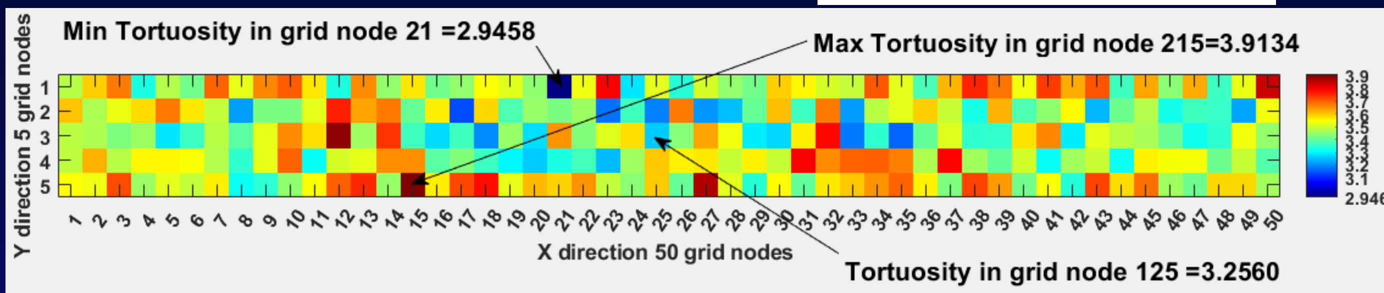


Avg = 0.19
Max = 0.22
Min = 0.16

Additional results

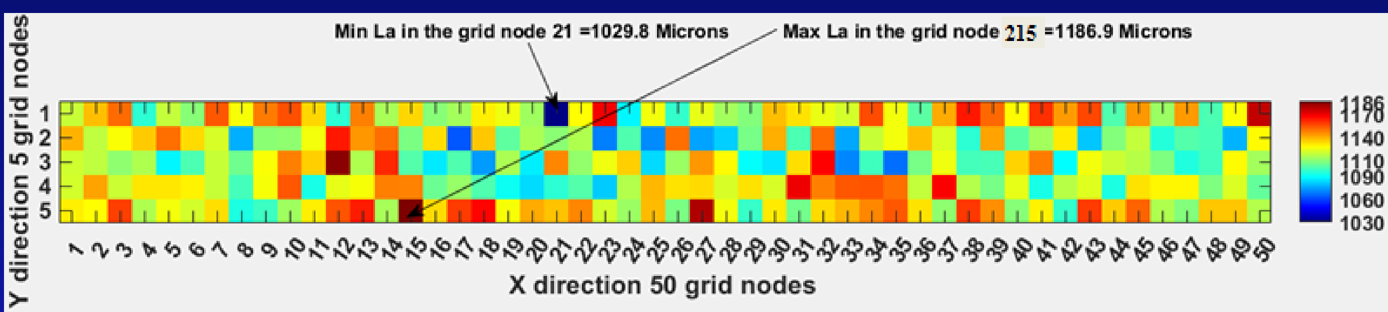
From code's correlations: Tortuosity, and La (actual flow path)

$$\tau_m = 1013.25 \frac{1}{2K_m} \frac{\varnothing_m^3}{(1-\varnothing_m)^2} \frac{1}{S_v^2}$$



Avg =3.4981
Max = 3.9134
Min =2.9458

Tortuosity= $\left[\frac{\text{Average tortuous distance traveled } (La)\ (\mu m)}{\textit{Straight-line distance between the endpoints of the flow path } (L)\ (\mu m)}\right]^2 = \left(\frac{La}{L}\right)^2$

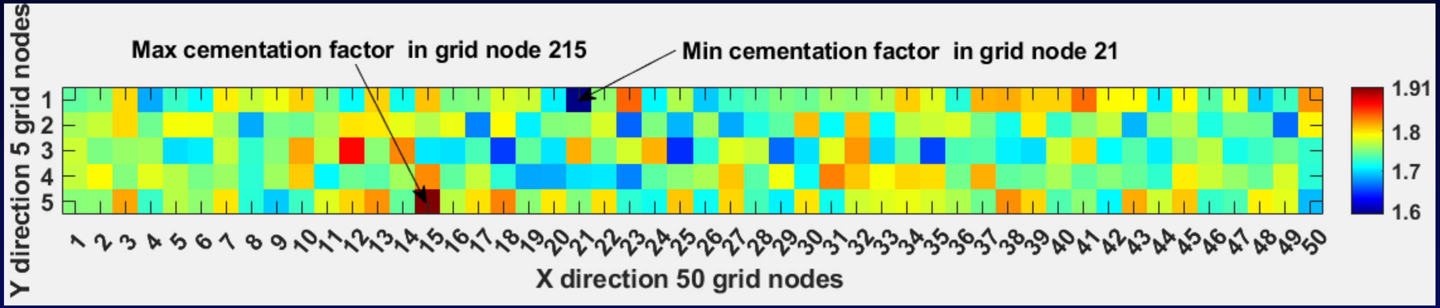


Avg La=1121.9 μm
Max= 1186.9 μm
Min= 1029.8 μm

Additional results

From code's correlation: Cementation factor (Archie)

$$C = 1 - \frac{\ln(\tau_m)}{\ln(\emptyset_m)}$$



Avg = 1.7543
Max = 1.1901
Min =1.5905

Other reservoir simulation's results :

A- Water oil ratio Vs. Time.

B- Injection, production, and total flow rates for oil and water Vs. Time.

C- Injection, production, and total oil and water volumes Vs. Time.

D- Water saturation destitution at and after BT Vs. Nodes locations.

E- Fractional flow Vs. S_w.

Future work

- Perform experiments in new chips (U1, V1, and N). Matching simulations and experiments. Calculate **Kx & Ky** for each node using LBM.

Chip Name	Specifications	Dimensions Length x width x height	Channel width	Uses
U	Random with Uniform channel width (homogenous networks)	3 cm x 3 mm x 14.6 μm	6 μm	History matching (Done)
U1		1.5 cm x 3 mm x 14.6 μm	6 μm	Experiment (W-O)
V1	Random with Vugs (heterogeneous Vuggy networks chip)	1.5 cm x 3 mm x 14.6 μm	8 μm	Experiment (W-O)
N	Random with Vugs (heterogeneous Vuggy networks) (a different kind of pore structure)	1.5 cm x 3 mm x 14.6 μm	6-8 μm	Experiment (W-O)

Conclusions

- Reservoir simulation results are very similar with the experimental results up to breakthrough time within 96% accuracy in oil recovery. This was achieved after adjusting the relative permeability curves.

- The viability of relative permeability functions, while consistent with conventional wisdom, require further investigation.

THANK YOU

QUESTIONS…..?