# ANALYZING THE OPEN FACE CONDITION AND NON-EQUILIBRIUM EFFECTS IN CO- AND COUNTER-CURRENT SPONTANEOUS IMBIBITION WITH EXPERIMENTS AND NUMERICAL SIMULATION

Rasoul Arabjamaloei[1], Douglas W. Ruth[1], Derrick Green[2], Dragan Veselinovic[2]
[1]Centre for Engineering Professional Practice and Engineering Education, University of Manitoba, Canada
[2] Green Imaging Technologies INC., Fredericton, NB, Canada

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## ABSTRACT
In this work a set of co- and counter-current spontaneous imbibition experiments were conducted on a sandstone core sample using Decane and $D_2O$ as displacing/displaced fluids. Using an Oxford Maran DRX-HF instrument, the saturation profiles of the fluids inside the core were measured and recorded during the experiments. The capillary pressure-saturation curves for the sample rock were obtained by MICP and centrifuge tests. The accumulative production of non-wetting phase, determined by integrating the obtained saturation profiles, shows a square root of time behavior while the whole process was seen to be affected by non-equilibrium effects at the inlet. It was assumed that all the production was from the upstream face in the counter-current case, and from the downstream face in co-current test. The experiments also showed an inlet water saturation of around 50%, which is in contradiction with the assumption of capillary continuity at the core face. The results were analyzed using an explicit simulator to obtain Corey-type relative permeability functions. It was found that the counter-current experimental results showed a close match between the simulated and the experimental results. Further, the relative permeability curves obtained by history matching of counter-current imbibition test results were used to simulate and predict the results for co-current imbibition test.

## INTRODUCTION
Both co-current and counter-current spontaneous imbibition are complicated two phase processes which are not yet well understood. One of the main processes involved in oil production from fractured reservoirs is spontaneous imbibition (SI) which is driven by capillary forces [1]. Experimental work has been done to study SI processes and obtain relative permeability and capillary pressure curves; however exact measurements of saturation distribution profiles are not very common [1, 2, 3]. The SI process could be modeled analytically if the proper sets of relative permeability curves are known for the porous medium. However, it is not yet known with certainty if a unique set of relative

permeability curves can be implemented for the mathematical modeling of all the processes happening in a porous medium. In the present work, experiments were run to measure the saturation distribution profiles in the sample core during co-current and counter-current spontaneous imbibition processes. The experimental data was then input to an explicit numerical simulator to achieve relative permeability curves by history matching. The core properties and the capillary pressure curves are taken from a previous study [4].

## THE EXPERIMENTAL STUDY

In this study two co- and counter-current SI tests were performed on a core sample of tight rock. Table 1 shows the rock type and properties.

Table 1: Rock properties of the sample used for co-current and counter-current experiments

| Rock type | Porosity (%) | Permeability (md) | Length (cm) | Cross Section ($cm^2$) |
|---|---|---|---|---|
| Sandstone | 23 | 2 | 2.5 | 9.61 |

Teflon tape was wrapped tightly around the cylindrical sample plug and then the plug was sealed with heat shrink plastic tubes. Figure 1 shows how the core was prepared before the experimental work and figure 2 shows a diagram of experiment set-up. A constant volume $D_2O$ reservoir is always maintained at the top of the sample by adding droplets. The length to diameter ratio of the sample might be small, that was due to the limitations of accessibility to big range of samples.

The two ends of the plug were open in co-current experiments while one end of the sample was sealed with liquid glue for counter-current test. The sample was fully saturated with decane by using centrifuge before the start of the experiment. That leads to zero initial water saturation which might affect the results of the experiment. To study the effect of initial water saturation another broad study is needed. Deuterium oxide ($D_2O$) was used as the injected fluid because this substance is not “seen” by the NMR apparatus. The NMR measurements were done using an Oxford Maran DRX-HF instrument at 30℃ and 2MHz frequency. Green Imaging Technologies (GIT) software was used to measure the decane saturation distribution. By proper design of the core holder it was possible to continue the experiment in the machine while the measurements were done.

The simulator uses 50 central grid blocks system with equal distances except for the boundary node which is a zero width block. The saturation change at each grid is calculated based on the flow rate difference across the block boundaries. The flow rates are calculated by modified Darcy’s law and gravity is ignored. The saturation profiles, the capillary pressure curves and rock and fluid properties were provided to the simulator as inputs. The program uses those data to find the best Corey-type relative permeability curves for the sample. The simulation was fully explicit and the upstream saturation of each grid block was used to calculate the Corey-type relative permeability of the corresponding block. Further details of the model may be found in [6].

History matches were achieved by minimizing the error between the experimental and simulated saturation profiles. Neither production data nor pressure data were used for the process of history matching.

## DATA ANALYSIS

Figure 3 shows the counter-current SI experimental data and the best fit curves resulting from the simulations. As observed in figures 3 and 4, there is a very good match between the experimental and simulation results, especially for the production curve. However, the measured saturation profiles might not show the well-known patterns expected for this displacement process. It is seen that water imbibes through the core very fast and compensate for the zero initial water saturation. It is also observed that the NMR readings don't show a strong water front during the co-current process at the early times. But it is seen that a front forms at latter times. The non-wetting phase production was calculated from NMR outputs. The relative permeability curves found for counter-current imbibition were next used to predict the results for the co-current imbibition test. Figure 5 shows the calculated relative permeability curves.

The objective was to determine if the history matched relative permeability curves are suitable for the co-current imbibition process. The simulator was used to produce and compare the saturation distribution and production curves. Figures 6 and 7 show the comparison of results.

## DISCUSSIONS AND CONCLUSIONS

As observed in figures 6 and 7, a Corey-type relative permeability curve can be used to numerically simulate the counter-current spontaneous imbibition. The predicted saturation distribution curves do not perfectly match the experimental results; however the predicted production has an excellent match with the experimental results. Because the NMR measurements take 1-2 minutes each time, this is a potential source of error in the saturation profiles and might cause the difference between experimental and simulation results. It is also observed in the experimental results that the inlet face saturation is changing with time and is not a unique value. This shows the role of non-equilibrium effects in a spontaneous imbibition process. However, at later times the saturation values stabilize and agree approximately with results predicted by the method of Arabjamaloei *et al* [7].

The co-current experimental production results did not show as close a match as for the counter-current case. This problem is likely related to the fact that in these experiments the two faces were open and production was happening at both faces as it was observed in the experiments; in the present experiments only the total production could be determined. Parts of the saturation curves show reasonable agreement; however, the upstream face saturation is not well predicted. This is further evidence that the face condition during spontaneous imbibition is poorly understood. It should be noticed that the produced decane floating on the top of the water reservoir in counter-current experiment or collected at the bottom in co-current experiment might affect the readings, but the effect was reduced by taking the decane out of the set-up every once in a while.

The results are encouraging since they show that, at least for one case, a single set of relative permeability curves based on counter-current test can be used to approximately predict the co-current test results.

## ACKNOWLEGEMENTS

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## REFERENCES

1. Mason, G. and N.R. Morrow, “Developments in Spontaneous Imbibition and Possible Future Work”, *Journal of Petroleum Science and Engineering*, (2013).
2. Baldwin, B.A., Spinler, B.A., 2002. In situ saturation development during spontaneous imbibition. Journal of Petroleum Science and. Engineering, 35 (1-2), 23–32.
3. Li, Y., Ruth, D., Mason, G., and Morrow, N.R., 2004, “Pressures acting in counter-current spontaneous imbibition”, Proceedings of the 8th International Symposium on Reservoir Wettability, Houston, TX, May 17-18.
4. Mason, G., Ferno, A., Morrow, N.R., Ruth, D.W., 2012, “Spontaneous Counter-Current Imbibition Outward from a Hemi-Spherical Depression”, Journal of Petroleum Science and. Engineering, 90-91 (July), pp.131-138.
5. Babak Salimifard, Douglas Ruth, Derrick Green, Dragan Veselinovic, “Developing a Model To Estimate Permeability from Other Petrophysical Data”, SCA2014-063, *International Symposium of the Society of Core Analysts*, (2014), Avignon, France, 8-11 September.
6. Ruth, D.W., Mason, G., Fernø, M.A., Haugen, A., Morrow, N.R., Arabjamaloei, R., “Numerical Simulation of Combined Co-Current/Counter-Current Spontaneous Imbibition”, International Symposium of the Society of Core Analysts, (2015), St.John’s, Newfoundland and Labrador, Canada, 16-21 August.
7. Arabjamaloei, R. and Shadizadeh, S. R., “A New Approach for Specifying Imbibition Face Boundary Condition in Countercurrent Spontaneous Imbibition”, *Petroleum Science and Technology*, (2010), 28(18): 1855-1862.

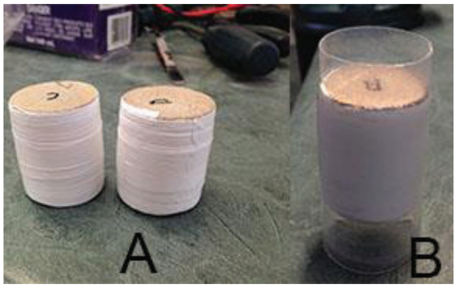

Figure 1: A: first step, the plugs are wrapped with Teflon tape, B: at the second step the cores are fitted inside a plastic tube

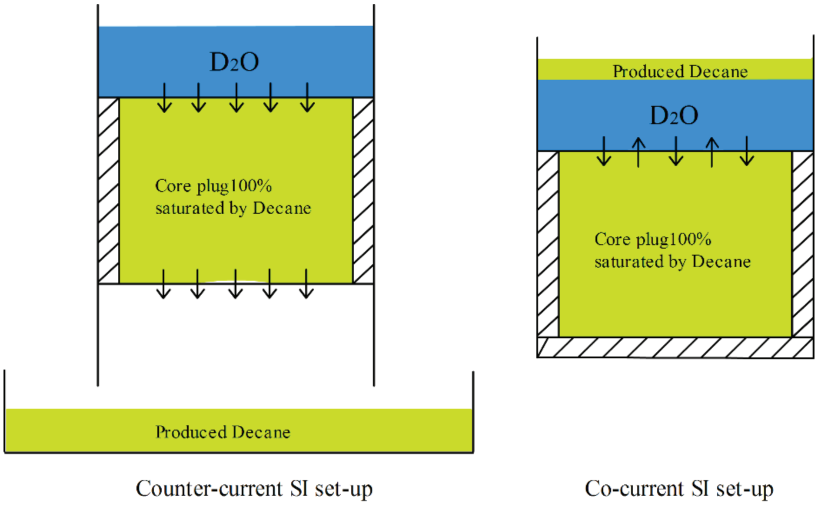

Figure 2: Diagram of the experimental set-up

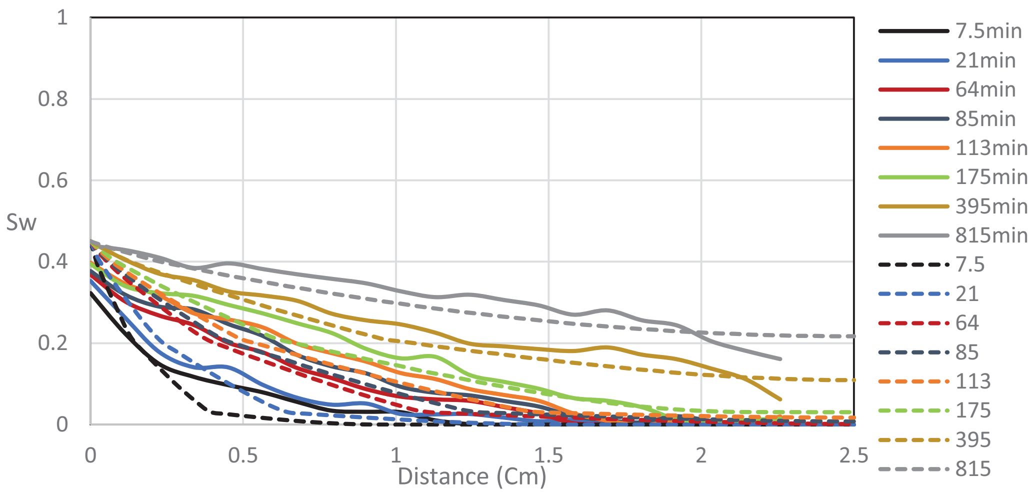

Figure 3: Comparison of the simulated (dash lines) and experimental (solid lines) saturation profiles for the counter-current spontaneous imbibition test

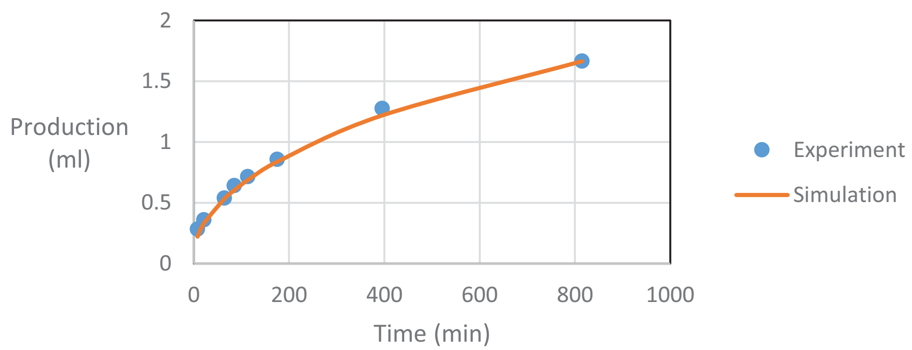


Figure 4: Comparison of non-wetting phase production data of experiments and simulation for counter-current test

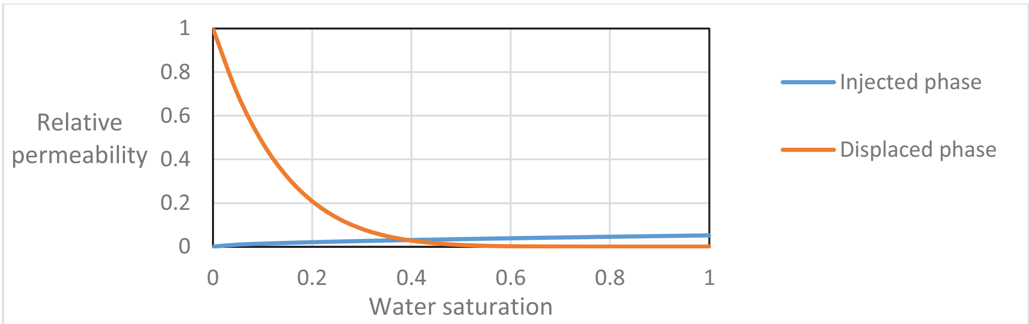


Figure 5: Relative permeability curves obtained by history matching the Counter-current imbibition test results. These relative permeability curves were also used to simulate non-wetting phase production of the co-current imbibition test.

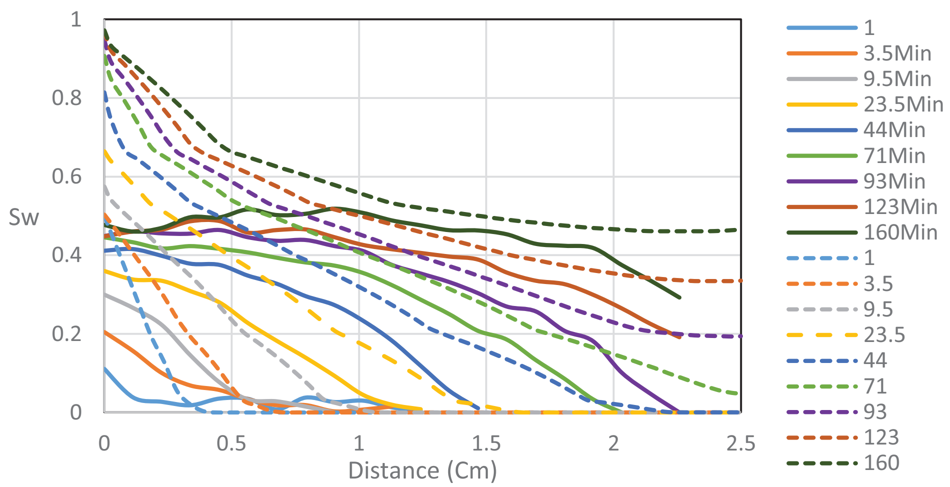


Figure 6: Comparison of the simulated (dash lines) and experimental (solid lines) saturation profiles for co-current spontaneous imbibition test

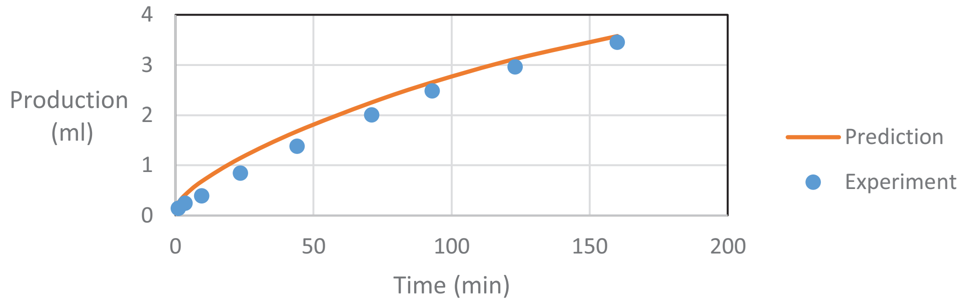


Figure 7: Comparison of non-wetting phase production data of experiments and simulation for co-current test