COMPARISON OF FOUR NUMERICAL SIMULATORS FOR SCAL EXPERIMENTS

Roland Lenormand1), Kjetil Lorentzen2), Jos G. Maas3) and Douglas Ruth4)

1) Cydarex, France; 2) PRORES AS, Norway; 3) Consultant, The Netherlands; 4) University of Manitoba, Canada

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ABSTRACT

There have been several benchmarks to test and compare reservoir simulators, but so far, there are not the equivalent exercises for numerical simulators used in the design and interpretation of SCAL laboratory experiments. In this study, we have compared four simulators used for the determination of relative permeability and capillary pressure from SCAL experiments. Several tests are performed in direct simulation (no history matching) with one or two fluids injected (generally called unsteady-state and steady-state or USS and SS, respectively), either without or with capillary pressure corresponding to a mixed wettability (positive and negative Pc in imbibition) sample. In addition, a centrifuge drainage experiment is included in the comparisons.

After discussion, the latest versions of the four simulators use the same boundary conditions and give similar results.

An important point that concerns both inlet and outlet is the notion that in the laboratory the plugs are in equilibrium with fluids in the end-pieces at the beginning of most experiments. If out-of-equilibrium conditions (spontaneous imbibition) occur, this phenomenon must be clearly identified because it leads to counter-current flow at the inlet and/or outlet, and possibly to negative pressure in the water phase. Normally, for SS and USS relative permeability measurements and centrifuge experiments, we assume that fluids are at capillary equilibrium at the beginning of the experiments.

For boundary conditions, two simulators use an extra grid block with $P_c=0$ to represent the fluids in the end-pieces. One simulator uses directly the boundary condition on the first and last grid block within the plug and the fourth simulator uses a zero width grid block set to a fixed saturation condition. We show that the three approaches lead to the same results for pressures and saturation inside the plug.

This study does not cover all the types of displacements, and we recommend that providers of SCAL simulators give more details concerning the type of boundary conditions and the way they are coded.

Tabular data for K_r, P_c and for the results will be available on the web sites of the authors, and on the SCA website.

INTRODUCTION

There have been several benchmarks to test and compare reservoir simulators (for instance the SPE Comparative Project [1], [2]), but so far, there are not the equivalent exercises for numerical simulators used in the design and interpretation of SCAL laboratory experiments. In this study, we have compared four simulators used for the determination of relative permeability and capillary pressure from SCAL experiments. Several tests are performed in direct simulation (no history matching) with one or two fluids injected (generally called unsteady-state and steady-state or USS and SS respectively), either without or with capillary pressure corresponding to a mixed wettability (positive and negative Pc in imbibition) sample. In addition, a centrifuge drainage experiment is included in the comparisons.

The first purpose of this paper is to compare the results of the different simulators, to point out the differences, and to explain these where possible. The second purpose is to provide a series of well documented reference cases that can be used by anyone to verify their own simulators. All the input data and results are provided.

THE TEST CASES

We have chosen 5 simple cases. Sample and fluid properties are documented in Table 1. Relative permeabilities follow a simple Corey function, with K_{rmax} and exponents also given in the table. We have tested two cases of capillary pressure curves for displacements, a smooth and a sharp curve, given in Table 2 and displayed in Figure 1. Relative permeabilities are displayed in Figure 2.

Case 1. Steady-State imbibition with smooth Pc curve.

Water and oil injected at increasing water fractional flow, followed by several “bumps” (only water injected for the bumps)

Case 2. Steady-State imbibition with sharp Pc curve.

Same as case 1 but with a sharper Pc curve

Case 3. Unsteady-State imbibition with smooth Pc curve

Only water injected at increasing flow rates

Case 4. Unsteady-state imbibition without capillary pressure (Buckley-Leverett)

Only one flow rate of water is injected. It is assumed that the Pc curve is negligible.

Case 5. Primary Drainage centrifugation

To test and compare the different calculation methods, we consider an analytical case where the local and the average Pc curves are well known. This case was presented by Chen and Ruth [6]. The distance between the oil entry face of the sample and rotation axis is 24.142 cm. For this well documented experiment, the centrifuge "b" parameter is equal to 0.5.

Conditions of experiments and output results

The experimental parameters, time at end of each step and flow rates or rotation speed, are given in Table 3. The outlet pressure has no influence on the results because liquid compressibility is neglected.

For all cases, the samples were assumed to have uniform porosity and permeability. For the imbibition displacements (cases 1 through 4), the samples are assumed to be at S_{wi} with a uniform saturation (after a porous plate displacement for instance). In the laboratory, the end-pieces (also called flanges or mandrels) have a void space or grooves to allow the uniform distribution of oil and water. Before the imbibition is started, these inlet and outlet spaces are filled with oil. For the centrifuge drainage (case 5), the sample is initially 100% saturated with water and placed in a core-holder full of oil. For this case, oil is present at the exit face of the plug.

In all simulations, the first output variable used for comparison is the average water saturation, which can be derived from the effluent production of oil in imbibition or water in drainage (centrifuge). The second output variable from the displacements is the pressure drop across the sample, as it would be measured with a differential pressure transducer tapped into the grooves of the end-pieces. All the simulators calculate water and oil pressures along the sample. The difference in phase pressure is determined by saturation using the P_c curve. However, the pressure transducer measures the pressure in the end-pieces, and this pressure can be either the water or the oil pressure at the face of the plug. This point proved to be the origin of differences between the simulators and will be discussed in the following sections.

NUMERICAL SIMULATORS

To be useful, it is necessary to provide the names of the simulators, as was done in the SPE benchmark [2]. The four numerical simulators have been developed by different teams working in Core Analysis. Their main specifications are the following:

CYDAR

CYDAR is a product of the French Institute of Petroleum (now IFPEN) and commercialized by CYDAREX (http://www.cydarex.fr/), a start-up of IFP, now an independent company.

The numerical scheme is fully implicit with an option for compressible flow (not used in this study). The boundary conditions are programmed as mathematical conditions on the frontiers of the first and last grids used for the simulation (there are no additional grid blocks to represent the end-pieces). The different SCAL experiments are pre-programmed (MICP, porous plate, centrifuge, spontaneous displacements, gravity drainage, centrifuge, semi-dynamic, etc.). The following boundary conditions are used for the displacements investigated in this study:

Outlet: For the imbibition displacements, it is assumed that there is oil in the outlet end-piece and spontaneous imbibition is not possible. The production of water before breakthrough is set to zero and the flow rate of oil is equal to the total flow rate injected (no compressibility). After breakthrough, P_c=0 because oil and water are continuous through the end face of the plug and are both present in the end-pieces with large radius of curvature. The measured pressure in the end-piece is equal to the imposed pressure (back pressure). Before breakthrough, this pressure is equal to the pressure of produced oil (continuous). After breakthrough, the measured pressure is equal to both pressures in oil and water. For the drainage centrifugation, production of oil is set to zero, only water is produced in the core holder that is filled with oil, and P_c is set to zero outside the plug.

Inlet: When two fluids are injected at constant flow rates, these two flow rates represent the boundary condition at the frontier of the first grid block. The measured inlet pressure in the end-piece is equal to the highest pressure. Because the radius of interfaces are very large in the grooves (P_c close to 0), the fluid with the highest pressure will invade the grooves and impose its pressure. This is similar when logging with the RFT tool in a well, the measured pressure in the transition zone is the pressure of oil since the fluid distribution by oil migration corresponds to a primary drainage with P_c>0 (rock initially water wet). When only one fluid is injected (USS, case 3), the 2016 version assumes that the measured pressure is the highest pressure, like in the SS case, if the inlet end-piece is filled with oil at the beginning of experiment. Previous versions assumed that the measured pressure was the pressure in water. This assumption will be discussed later in this paper.

PORLAB

Porlab is a numerical simulator developed by D&B Ruth Enterprises to allow a wide range of implementations of modelling techniques. It may be run in either implicit or explicit modes – the explicit mode was used in the present study. The boundaries are modelled by zero-wide grid blocks that can be set to any saturation required to model the physical situation. For example, the production face can be modelled as one of three scenarios: contact with the injected component (a flushed face or production into a plenum), contact with the displaced component (a flushed face) or contact with both components (a grooved flange). For the USS experiments, the inlet pressure is assumed to be the pressure in the injected component while the downstream pressure is assumed to be zero in both components. For the SS cases, the inlet pressure is assumed to be the pressure in the water. For the SS and USS cases, a uniform grid system is used; for the centrifuge case, a refined grid system is used that ensures a grid boundary occurs at the exact location of the equilibrium displacement front at each speed. The simulator can account for counter-current spontaneous imbibition at both ends of the sample (production of oil at the inlet face if the capillary pressure requires it or additional production at the outlet face if there is a source of the injected fluid, that is, water imbibition at the outlet face in a water flood). However, both of these phenomena can be suppressed by the modeler. The present study utilized a model where both fluids had zero pressure in the zero width outlet grid block and counter-current spontaneous imbibition was suppressed.

SCORES

Only a summary is presented here - details are presented in previous SCA papers by Maas *et al* [3, 4]. Grid blocks are refined towards entry and exit faces of the core plug. At each side of the plug, one extra grid block is added to mimic the end-flanges with grooves. It is safe to assume that in the grooves P_c equals zero, so for those extra blocks outside the plug, P_c is set to zero for all time steps. Permeability and porosity in the extra blocks are set to the same values as in the core plug. At initialization, S_w in the extra grid block at the entry face is set to S_{wi}, both for simulations in drainage and in imbibition mode. In the extra block at the exit, S_w is initialized at S_w=0 for imbibition and at S_w=1 for drainage mode. The pressure drop is reported as the pressure difference between the external blocks (where P_c=0, so both phases have the same pressure). The flow equations are solved in fully implicit mode. The simulator is available free-of-charge at http://www.jgmaas.com and handles USS (both liquid-liquid and gas-liquid), SS, Centrifuge, Porous Plate, Continuous Injection and as of recently, MICP [5].

SENDRA

Sendra is a core flood simulator developed and maintained by PRORES AS (www.prores.no/sendra/). The simulator is a fully implicit two-phase core flow simulator specially designed to simulate and verify SCAL experiments. It covers all common experimental approaches including USS and SS flow experiments, single- and multi-speed centrifuge experiments, as well as porous plate experiments. It can be utilized for oil-water experiments as well as gas-oil or gas-water experiments, for both imbibition and drainage processes. A third stagnant (immobile) phase may also be present in simulations. Sendra also handles compressibility.

In Sendra, inlet and outlet boundary conditions are modelled using an extra grid block to represent the upstream and downstream “void”. The outlet boundary conditions with an extra grid block have always been present in Sendra; however the extra grid block at the inlet was added for the release of Sendra 2014.3 in early 2015. Both the inlet and outlet grid block are modelled with negligible size and P_c=0, to make sure that phase pressures are equal. Permeability is set to a large value to avoid any significant pressure drop in the inlet and outlet grid block. Porosity is set to 1.0. Upon initialization of USS experiments, saturation in the inlet is set to S_w=1 for water-oil imbibition and S_w=0 for water-oil drainage. For SS experiments, inlet saturation S_w corresponds to the first fractional flow rate, (*e.g.* for an water-oil imbibition starting with injection of oil only would result in a fractional flow rate of water equal to zero and from that the inlet saturation would be set S_w=0). The outlet saturation uses S_w equal to the core at initialization to ensure equilibrium. The pressures across the core and inlet/outlet are set constant when initializing, with individual phase pressures given by the P_c curve.

The pressure drop is recorded as in SCORES, taken as the difference in pressures between the inlet and outlet grid block where phase pressures are equal.

RESULTS

The results of the numerical simulations are displayed in Fig. 3 to 11 for average saturations and differential pressures. In all cases, the results of all four simulators are essentially the same. All the curves are superimposed; the only very small differences observed when zooming come from the number of points used to display the results. Some discrepancies have been observed for case 3 with the original versions of the softwares. After discussion, it was decided to use a common inlet experimental condition. Using this condition leads to results in good agreement among the four simulators. However, it is very important than experiments be conducted in such a manner that the inlet boundary condition is well defined so that there is no confusion as to the phase in which the inlet pressure is being measured.

DISCUSSION

Cases 1 and 2 give very similar results for both pressure difference and average saturation. That implies that the three different implementations of the boundary conditions in the four simulators are equivalent.

At inlet, this equivalence can be demonstrated. In Figure 12a) pressure in the inlet end-piece, P, is smaller than P_{in_oil} (phase pressure of oil at the inlet face inside the core), there will be production of oil from the sample to the end-piece (the flow follows the opposite of gradient), incompatible with the injection of oil into the sample. Because oil is injected through the sample, P must be larger than P_{in_oil} and if the permeability of the end-piece is very large, the pressure drop is negligible and P= P_{in_oil}, Figure 12b). Consequently, the two models are equivalent.

At outlet, the condition P_c=0 in an extra grid block before breakthrough gives similar results as the condition of zero water flow rate. P_c=0 implies a large water pressure gradient at the outlet, but there is no flow of water because spontaneous imbibition is not allowed. For all the approaches, the consequence is zero water flow rate at the outlet.

Case 3: For this case, the inlet boundary condition is not straightforward. Water is injected at the end of primary drainage. At S_{wi} (= 0.2), capillary pressure is positive (11.5 bar). That means that pressure in water is -11.5 bar with respect to the oil pressure (by definition, $Pc=P_{oil}-P_{water}$). Water is injected at a low flow rate (1cc/h) and oil is displaced at this low flow rate. The numerical simulation shows that the pressure drop in oil along the sample is around 0.013 bar. Consequently, at time t=0, the pressure in water at the inlet face is negative and around -11.5 bar. Figure 13a and b display the pressure profiles at time, t = 0.5 hour, when water has already partially invaded the sample. At the inlet face inside the sample, the pressures in oil and water differ and water pressure is still negative.

The discussion was about which pressure P is measured by a pressure sensor in the inlet end-piece (Figure 13c). Initially CYDAR and PORLAB assumed that the end-piece inlet pressure was equal to the pressure in water, because water is injected and should be continuous. SCORES assumes P_c=0 just outside the core plug in the extra grid block, equivalent to taking the highest pressure (see the discussion for Cases 1 and 2 and Figure 12). As P_c=0, phase pressures are equal and there is no need to decide which of the two phase pressures to use.

After discussion, the authors agreed that pressure should be the highest pressure (corresponding to Pc=0) if the experiment is started at capillary equilibrium with the inlet end-piece filled with oil. If inlet end-piece is filled with water or if water is injected through a porous plate (not the condition of this case), the measured pressure is water pressure represented by the dashed line in Figure 8.

For PORLAB, the question of which pressure is measured in the end-piece may rely on experimental design. If the end-piece is initially filled with oil, the original pressure reading will be the oil pressure (during the stage where water has not yet contacted the sample). Once water contacts the sample and if the sample is water wet, counter-current spontaneous imbibition could occur. In this case, the oil would be discontinuous and the pressure measured would likely be the water pressure. However, this process may be unstable, with produced oil blocking the flow of water to the sample and consequently being pushed back into the sample. If this occurs, the continuous fluid could once again become the oil. However, oil may not be present in the end-piece and, depending on the construction of the simulator; the only prediction of oil pressure is for the first grid block inside the sample. In situations where counter-current imbibition can occur, this pressure is definitely not the pressure that would be measured in oil in the end-piece. It would be most prudent to caution the user of numerical simulators of the difficulty of pressure predictions at early times.

For SENDRA, Sendra allows a spontaneous imbibition and uses S_w=1 in the extra grid block at time, t=0, for water-oil imbibition. Due to this, Sendra experiences a quick transient, when water spontaneously imbibes into the core. This is due to the pressure gradient from the inlet grid block to the next being larger than the pressure imposed from injecting at such a low rate. Sendra allows for manual sizing of the inlet grid block (with a default value of dx=0.1mm), and setting this to a lower value than the default would probably reduce (or entirely remove) the time of negative pressures, as the pressure from injection would build faster in a smaller grid block. However, this negative transient has no effect on the interpretation of laboratory experiments.

For CYDAR, the initial version of the code assumed that the measured pressure is the pressure in water, because water is injected and is assumed to be continuous. This would be true if the end-piece is filled with water. However, the purpose of the experiment is not to realize a counter-current imbibition in the inlet end-piece. Consequently, both experiment and simulation should start in an equilibrium state, with the inlet end-piece filled with oil. The measured pressure is the pressure in oil because it is the highest pressure. When water is injected inside the end-piece, water is disconnected and the measured pressure remains the pressure in oil (highest pressure).

For SCORES, similar to CYDAR, the purpose was not to simulate a possible counter-current process at the inlet. In addition, assuming Pc=0 in the extra grid block is equivalent to assuming pressure equilibrium in the inlet end-piece at time t=0. This condition is equivalent to the new condition of pressure in oil (highest pressure) taken in CYDAR.

CONCLUSION

The following conclusions are based on comparisons of four different simulators:

1) Extra grid blocks and/or different mathematical boundary conditions on the frontier of the grid blocks lead to the same result.

2) When using the same boundary conditions, all the numerical simulators give similar results with accuracy much higher than experimental accuracy.

3) For USS case 3, there is a strong need for a verification of the experimental procedure to be sure that the fluids present in the grooves of the end-pieces at the beginning of the experiments correspond to an equilibrium condition (Pc=0). It is especially recommended to start with oil in the inlet end-piece.

The purpose of this paper is also to allow anyone using simulators, either the four described in this paper or in-house simulators, to compare their results. Tabular data for K_r, P_c and for the results will be available on the web sites of the authors and on the SCA website.

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Table 1-Properties of samples and fluids used for the simulations

		case 1	**case 2**	**case 3**	**case 4**	**case 5**
type of experiment		SS + bumps	SS + bumps	USS	USS	centrifuge
type of displacement		imbibition	imbibition	imbibition	imbibition	primary drainage
disposition		horizontal	horizontal	horizontal	horizontal	
length	cm	8	8	8	8	10
Diameter	cm	4	4	4	4	4
Base permeability	mD	100	100	100	100	100
porosity	frac	0.25	0.25	0.25	0.25	0.25
water viscosity	cP	1	1	1	1	1
water density	g/cm^3	1	1	1	1	1
oil viscosity	cP	5	5	5	1	5
oil density	g/cm^3	0.8	0.8	0.8	0.8	0.8
initial Sw	frac	0.2	0.2	0.2	0.2	1
final Sw	frac	0.8	0.8	0.8	0.8	0.3
Krw_max	frac	0.5	0.5	0.5	0.5	1
Kro_max	frac	0.5	0.5	0.5	0.5	1
Corey exponent water		3	3	3	3	3
Corey exponent oil		3	3	3	3	2
Pc curve		Pc smooth	Pc sharp	Pc smooth	Pc = 0	Pc centrifuge

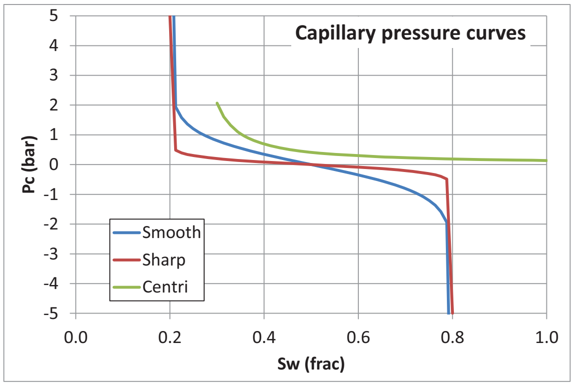

Figure 1 - Capillary pressures used for the simulations

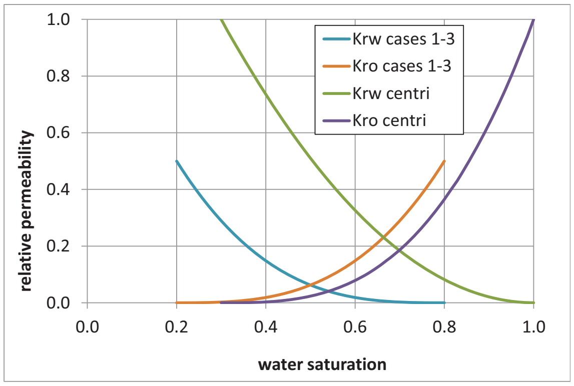

Figure 2 - Relative permeabilities used for the simulations

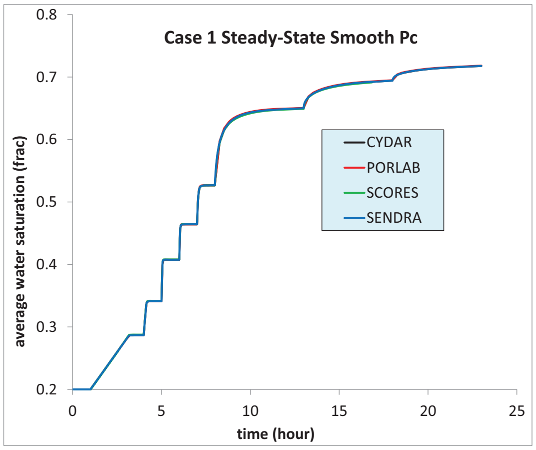

Figure 3 - Case 1 - Steady-State smooth Pc -Average saturation

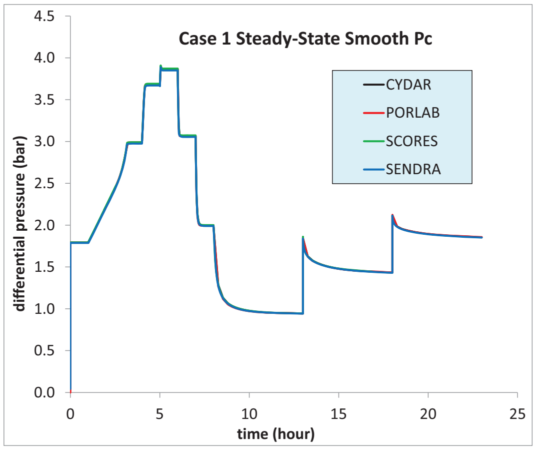

Figure 4 - Case 1 - Steady-State smooth Pc –Differential pressure

Table 2 - Capillary pressure curves used for the simulations (pressures in bar)

Sw	Smooth	Sw	Sharp	Sw	Centri
0.2000	11.5129	0.2000	5.0000	0.3000	2.0680
0.2122	1.9379	0.2122	0.4844	0.3143	1.6034
0.2245	1.5784	0.2245	0.3946	0.3286	1.3244
0.2367	1.3655	0.2367	0.3414	0.3429	1.1161
0.2490	1.2101	0.2490	0.3025	0.3571	0.9638
0.2612	1.0874	0.2612	0.2719	0.3714	0.8494
0.2735	0.9851	0.2735	0.2462	0.3857	0.7637
0.2857	0.8958	0.2857	0.2240	0.4000	0.6890
0.2980	0.8172	0.2980	0.2043	0.4143	0.6290
0.3102	0.7459	0.3102	0.1865	0.4286	0.5805
0.3224	0.6804	0.3224	0.1701	0.4429	0.5364
0.3347	0.6200	0.3347	0.1550	0.4571	0.4987
0.3469	0.5629	0.3469	0.1408	0.4714	0.4662
0.3592	0.5094	0.3592	0.1274	0.4857	0.4395
0.3714	0.4583	0.3714	0.1146	0.5000	0.4140
0.3837	0.4091	0.3837	0.1022	0.5143	0.3906
0.3959	0.3620	0.3959	0.0905	0.5286	0.3716
0.4082	0.3161	0.4082	0.0791	0.5429	0.3532
0.4204	0.2718	0.4204	0.0679	0.5571	0.3368
0.4327	0.2285	0.4327	0.0571	0.5714	0.3216
0.4449	0.1857	0.4449	0.0464	0.5857	0.3083
0.4571	0.1439	0.4571	0.0360	0.6000	0.2960
0.4694	0.1024	0.4694	0.0256	0.6143	0.2838
0.4816	0.0613	0.4816	0.0153	0.6286	0.2733
0.4939	0.0205	0.4939	0.0052	0.6429	0.2631
0.5061	-0.0205	0.5061	-0.0052	0.6571	0.2539
0.5184	-0.0613	0.5184	-0.0153	0.6714	0.2457
0.5306	-0.1024	0.5306	-0.0256	0.6857	0.2372
0.5429	-0.1439	0.5429	-0.0360	0.7000	0.2300
0.5551	-0.1857	0.5551	-0.0464	0.7143	0.2229
0.5673	-0.2285	0.5673	-0.0571	0.7286	0.2162
0.5796	-0.2718	0.5796	-0.0679	0.7429	0.2101
0.5918	-0.3161	0.5918	-0.0791	0.7571	0.2039
0.6041	-0.3620	0.6041	-0.0905	0.7714	0.1988
0.6163	-0.4091	0.6163	-0.1022	0.7857	0.1931
0.6286	-0.4583	0.6286	-0.1146	0.8000	0.1880
0.6408	-0.5094	0.6408	-0.1274	0.8143	0.1829
0.6531	-0.5629	0.6531	-0.1408	0.8286	0.1791
0.6653	-0.6200	0.6653	-0.1550	0.8429	0.1750
0.6776	-0.6804	0.6776	-0.1701	0.8571	0.1709
0.6898	-0.7459	0.6898	-0.1865	0.8714	0.1659
0.7020	-0.8172	0.7020	-0.2043	0.8857	0.1631
0.7143	-0.8958	0.7143	-0.2240	0.9000	0.1590
0.7265	-0.9851	0.7265	-0.2462	0.9143	0.1559
0.7388	-1.0874	0.7388	-0.2719	0.9286	0.1521
0.7510	-1.2101	0.7510	-0.3025	0.9429	0.1490
0.7633	-1.3655	0.7633	-0.3414	0.9571	0.1470
0.7755	-1.5784	0.7755	-0.3946	0.9714	0.1439
0.7878	-1.9379	0.7878	-0.4844	0.9857	0.1411
0.8000	-11.5129	0.8000	-5.0000	1.0000	0.1380

Table 3 - Experimental procedure

	time (hour)	Q water (cc/hour)	Q oil (cc/hour)
case 1 and 2	1	0	100
	4	1	99
	5	10	90
	6	40	60
	7	70	30
	8	90	10
	13	100	0
	18	200	0
	23	300	0
case 3	10	1	0
	13	10	0
	16	70	0
	21	200	0
	26	300	0
case 4	1.1	200	0
case 5 Centrifuge	**time (hour)**	**speed (rpm)**	
	5	200	
	10	500	
	15	1000	
	20	2000	
	25	3000	
	30	5000	

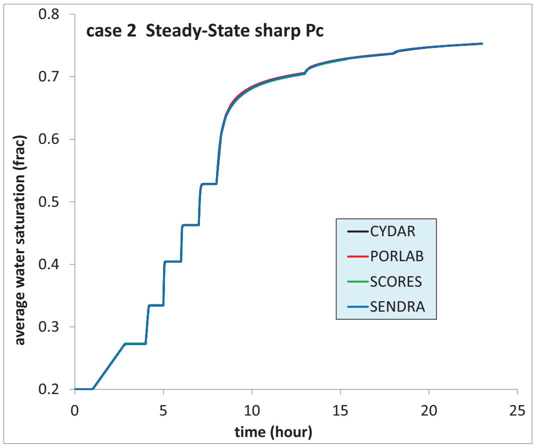

Figure 5 - Case 2 - Steady-State sharp Pc –Average water saturation

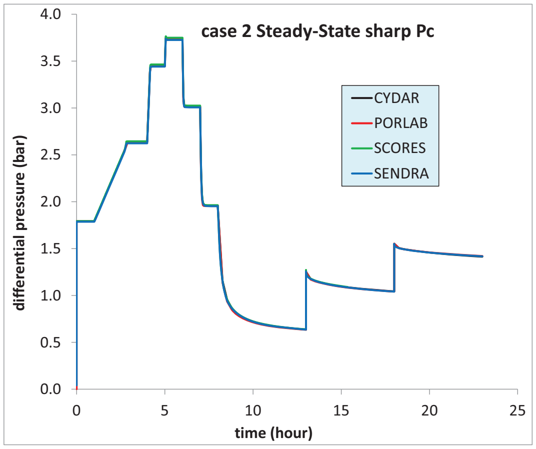

Figure 6 - Case 2 - Steady-State sharp Pc –Differential pressure

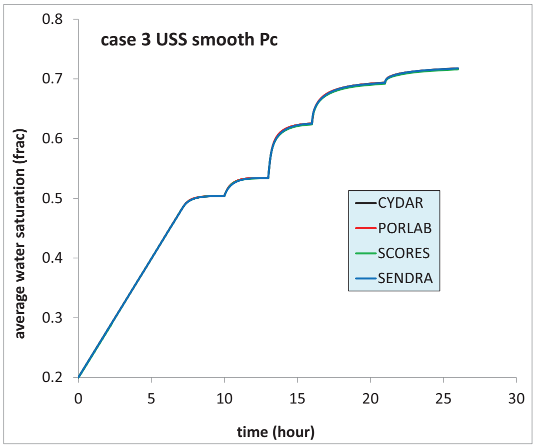

Figure 7 - Case 3 - Unsteady-State smooth Pc -Average water saturation

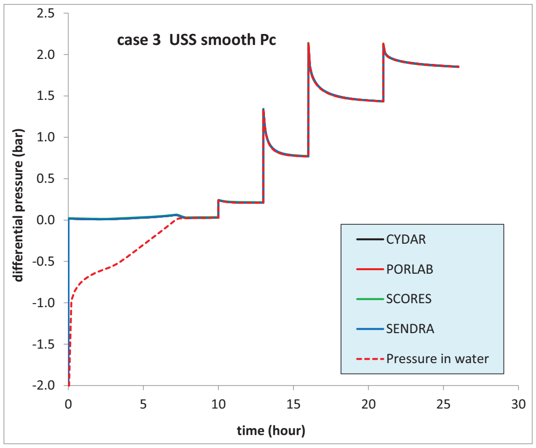

Figure 8 - Case 3 - Unsteady-State smooth Pc – Differential pressure.

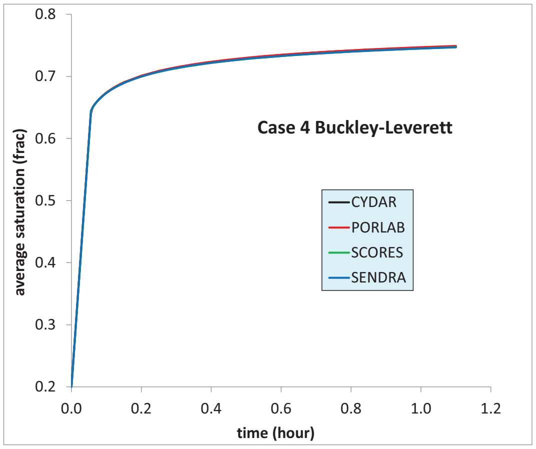

Figure 9 - Case 4 - Buckley-Leverett. Average water saturation

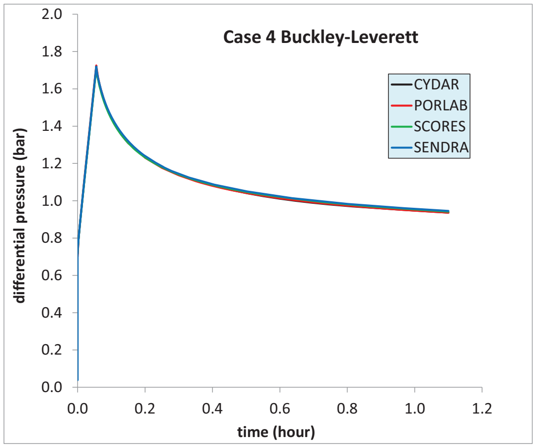

Figure 10 - Case 4 - Buckley-Leverett. Differential pressure

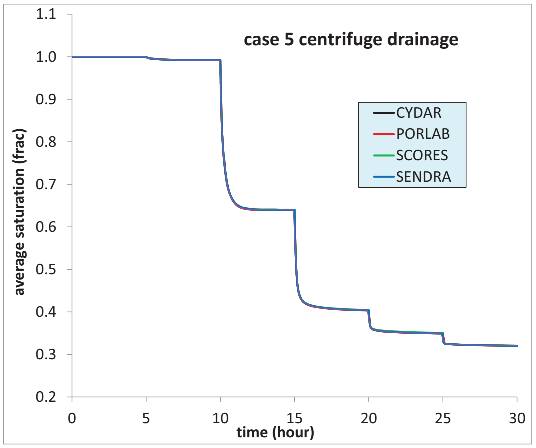

Figure 11 - Case 5 - Average water saturation during centrifuge drainage

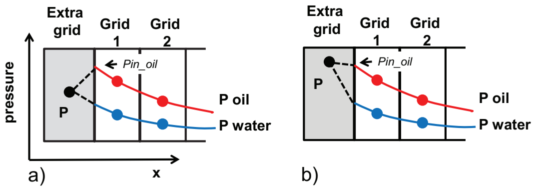

Figure 12 - Sketch of end-piece pressure, P, compared to oil and water pressures inside the sample:
a) if P< Pin_oil, there will be production of oil from the sample to the end-piece, incompatible with the injection of oil into the sample;
b) P must be larger than Pin_oil and if the permeability of the end-piece is very large, the pressure drop is negligible and P= Pin_oil

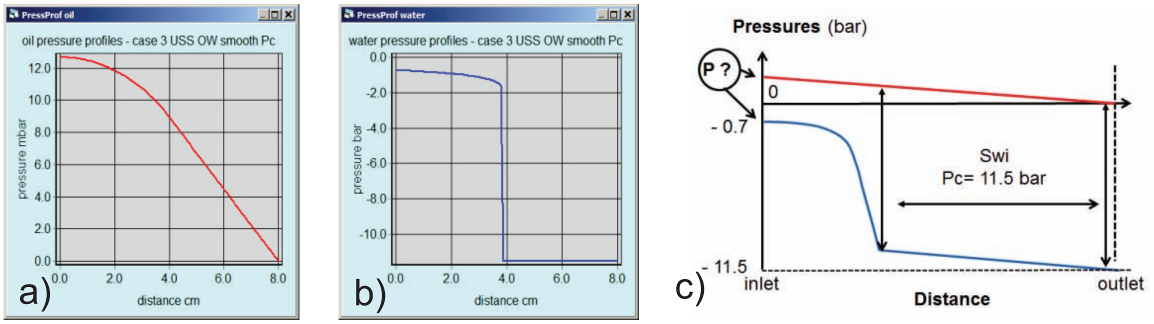

Figure 13- Case 3: injection of water a) profile of oil pressure at time = 0.5 hour; b) profile of water pressure; c) sketch of the oil and water pressures along the samples. The problem is to define the end-piece pressure either as the oil or water pressure at inlet