OPEN SOURCE SIMULATOR DUMU^x AVAILABLE FOR SCAL DATA INTERPRETATION

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ABSTRACT

An important problem in the interpretation of special core analysis (SCAL) laboratory data is that during relative permeability measurements a strong interference exists with the capillary forces. In the small core samples used in the lab, these forces play a role that is much different from what occurs on the scale of the field. As an example: the residual oil saturations may appear in the lab to be some 10 to 15 saturation units higher than they really are in the field. *Vice versa*, during capillary pressure measurements, the relative permeabilities interfere.

To unravel this interference, simulations of the experiments are necessary. DuMu^x, dumux.org, is an open-source simulator for flow and transport processes in porous media, based on the Distributed and Unified Numerics Environment DUNE. Its development started in January 2007 at the University of Stuttgart and is still ongoing. DuMu^x is part of the OPM (Open Porous Media) initiative.

The paper highlights how DuMu^x has been adapted to simulate SCAL experiments. These include flooding and centrifuge measurement techniques, as well as experiments using a porous plate. DuMu^x has been verified against analytical calculations and against MoReS, Shell's proprietary simulator. Subsequently, based on simulations, a detailed analysis is presented of experimental issues around two methods used in the industry to measure the resistivity index and capillary pressure: the Porous Plate method, and the Continuous Injection method. Simulations are compared to actual laboratory data.

A web-based user interface to DuMu^x is made available that can be used free of charge, fully in line with the philosophy of free software licensing under GPL(2).

INTRODUCTION

Field development employs dynamic models to predict reservoir behaviour over tens of years. The dynamic models are in essence an extension of static reservoir models. That extension is made by inserting basic flow parameters such as relative permeabilities, capillary pressure and residual oil saturations. These flow parameters are generated in the laboratory by special core analysis (SCAL) experiments.

One of the most common SCAL experiments is the Welge or UnSteady-State (USS) technique. A core plug is prepared at an initial water and oil saturation, representative of the relevant reservoir unit. Subsequently, water is injected to mimic a water drive. The pressure drop is measured together with the produced oil and water. From these data after water breakthrough, the relative permeability to water and oil as a function of saturation can be derived through an analytical approach like the JBN [1] method. A limitation of the USS technique is that the relative permeabilities can only be determined for saturations above the Buckley-Leverett [2] shock-front saturation. This limitation is overcome by the Steady-State method where oil and water are injected simultaneously, at varying fractional flow. Relative permeabilities are derived through a straight inversion of Darcy's equation for each phase. However, both JBN and the inversion of Darcy's equation assume that capillary forces are absent. Particularly at saturations close to the residual oil saturation S_{orw}, this assumption is violated and the oil production is severely hampered by a capillary end-effect inside the core plug. Eventually, oil flow will stop due to the capillary forces, while the oil saturation is actually significantly above residual. Since the analytical methods mentioned above are unaware of capillary forces, zero oil flow incorrectly is interpreted as reaching residual oil saturation. This remaining oil saturation is often 10 to 15 saturation units higher than true residual. Clearly, this data interpretation problem is a big issue when IOR or EOR targets need to be established in mature water flood fields.

To account for the capillary end effect, capillary (imbibition) curves need to be measured. Porous Plate (PP) experiments and centrifuge experiments are used for that. The measurement protocols require an equilibration time at each pressure step in PP or at each speed step of the centrifuge to establish hydrostatic equilibrium at zero flow. A direct data inversion in PP or a somewhat more involved method like Hassler-Brunner [3] for centrifuge experiments will then deliver the capillary pressure function. It is interesting to note that these analytical data inversions to extract capillary pressure from production data in PP or centrifuge, assume that relative permeabilities can be neglected. Similar to the situation in relative permeability measurements, the assumption is certainly violated at residual oil, using finite equilibration times. To properly analyse the situation, one would need to measure these relative permeabilities first. Therefore, we see that in SCAL experiments relative permeability and capillary pressure are mutually interfering and obscure the true data particularly for saturations close to residual oil, and *vice versa* close to connate water.

Initially there have been attempts to expand the analytical procedures by introducing (estimates for) correction functions. Eventually, it was understood by several authors [a.o. 4, 5, 6] that the interference between relative permeabilities and capillary pressure was best unraveled by forward modeling of the experiments. An iterative procedure is used to arrive at a simultaneous match of flow and PP or centrifuge experiments with one common data set for relative permeability and capillary pressure. To promote this approach, at no cost Shell in the late nineties made available SCORES, a web-based interface to MoReS, Shell's proprietary simulator. SCORES allowed simulation of USS

(imbibition only), SS and centrifuge multi-speed and single-speed experiments [7]. This service was available until 2010. Meanwhile, very few commercial simulators are suitable for simulation of SCAL experiments on the scale of the laboratory *i.e.* on core plugs of just a few centimeters long and wide [8].

The present paper presents a successor to the Shell tool, now based on the open source simulator DuMu^x, extending the original tool to incorporate not only USS, SS and centrifuge, but also PP and Continuous Injection (CI) [9]. DuMu^x includes the measurement of the resistivity index (RI) for PP and CI, to facilitate a detailed analysis of RI laboratory measurements. Another extension is that USS now also can be run in drainage mode. The new SCORES internet interface again is available at no cost.

In this paper, we will first discuss the general characteristics of DuMu^x. Subsequently, modeling details are presented for the USS, SS, centrifuge, PP and CI methods. We will then present a validation of DuMu^x, comparing simulations with analytical results and results obtained previously with MoReS. We will also present results for PP and CI and relate these to actual laboratory measurements.

DUMUX CHARACTERISTICS

DuMu^x is a simulator for flow and transport processes in porous media [10], licensed under the terms and conditions of the GNU General Public License (GPL) version 2 or later [11]. Stable releases are available for download [12], and anonymous read-access to the Subversion repository is granted. DuMu^x is built on top of DUNE, the Distributed and Unified Numerics Environment, a modular toolbox for solving partial differential equations with grid-based methods [13]. The development of DUNE is a joint effort of five research groups located at German and English universities. Its user base is growing, and a first DUNE user meeting in October 2010 was attended by 30 scientists from 16 research groups out of 4 European countries.

The DUNE module DuMu^x includes several standard models of varying complexity, ranging from stationary isothermal single-phase single-component flow to transient non-isothermal multi-phase compositional flow. Active research is currently undertaken to include multi-scale and multi-physics concepts, as well as non-standard formulations like multiple continua approaches or models involving interfacial area as a primary state variable. All models employ efficient nonlinear solvers in close combination with sophisticated time step management. The capabilities of DUNE are heavily exploited to offer various spatial discretization schemes as well as the possibility of parallel computations. The applications currently targeted by DuMu^x include fuel cells, groundwater remediation, evaporation from partially saturated soils, CO_2 storage, and drug delivery into human tissue. Several scientists from diverse areas of expertise (computer science, engineering, mathematics) are involved in the code development. Since the first release in July 2007, over 200 certified release downloads have been counted, and direct contact to several users has been established. As part of the Open

Porous Media (OPM) initiative [14], the development of DuMu^x is partially funded in a joint industry project.

The numerical models implemented in DuMu^x can be distinguished as decoupled semi-implicit and coupled fully-implicit approaches. For the SCAL simulation of this study, the latter approach is used for modeling two-phase immiscible isothermal porous media flow and transport. As spatial discretization, a vertex-centered finite volume scheme (box method) is used. An implicit Euler scheme is applied for the temporal discretization.

MODELING DETAILS

Similar to reservoir simulation models, a SCAL core plug needs to be discretised into cells or grid blocks. MoReS employs a finite difference scheme where equations are solved at the centre points of the grid blocks. DuMu^x employs a control volume finite element scheme and the coupled material balance and flow equations are solved at each node on the grid, where the nodes are located at the corner points of each cell or grid block. Both MoReS and DuMu^x are fully implicit simulators.

Gridding

We have chosen a common set-up for the gridding for all experiments. Based on previous experience with MoReS, the core plug in a SCAL experiment is divided into rectangular cells. Basically the grid blocks are in 1-D, but each has nodes left and right if the plug is vertical. The solutions of the equations on the left and right sides will be identical. The bulk of the grid blocks are evenly spaced by a constant Δz, z being the vertical co-ordinate. Near in- and out-flow ends, spacing is refined over 4 grid blocks, according to 0.1 Δz (at outer end), 0.2 Δz, 0.4 Δz and 0.8 Δz [7]. The user specifies the total number of blocks N for the core plug and DuMu^x has been adapted to calculate the appropriate Δz such that, with the refinement cells included, the total length of the core plug is covered with N blocks.

Gravity

For imbibition or drainage, injection is always set for gravity stable displacement in line with laboratory practice. For ease of programming and code maintenance, production is always at the lowest numbered block and injection is always at the highest numbered block. To make this possible, the sign of gravity is flipped when choosing between drainage and imbibition to account for the density difference. The user may opt to have the plug mounted horizontally, in which case g is set to zero.

As mentioned above, the gridding of the core plug is common to all SCAL experiments. The differences between the simulation set-ups are in the choice for boundary conditions. We will discuss these for each experiment individually.

UnSteady State Simulations

A constant flux boundary condition is programmed at the in-flow end and a constant pressure boundary condition is programmed at the out-flow end. Capillary pressure at the outer nodes is set identically to zero to simulate the chamber in the flanges[1]. All the other nodes have the read-in capillary pressure. Other user input includes the water and oil relative permeability k_{rw} and k_{ro} tables as a function of water saturation S_w, absolute permeability K_{abs}, porosity, water and oil density and viscosity and IFT between water and oil. IFT is used when the user specifies a dimensionless table for the Leverett-J [15] function, rather than a direct table of the capillary pressure.

DuMu^x calculates at each time step the individual phase pressure at each node. Consequently, the pressure difference between the (first+1) node and the (last-1) represents the pressure difference that would be measured in the laboratory when water-wet and oil-wet filters in pressure taps are used, while the pressure difference between the outer nodes corresponds to the pressure difference measured in the laboratory with pressure transducers connected without filters to the outer flanges. At each time step the differential pressures, injection and production flow rates, cumulatives and mean saturation is printed into an Excel file. At time levels indicated by the user, a saturation profile along the core is printed into a second Excel file.

As an extension to the original SCORES set-up, the USS simulations allow both imbibition (injection of water) and drainage (injection of oil), under gravity stable conditions.

Steady State Simulations

As with USS, a constant flux boundary condition is set at the in-flow face and a constant pressure at the out-flow face, and zero capillary pressure is set at both end-faces. Differential pressure, data on produced liquids and saturation profiles are printed into Excel files as for USS.

Centrifuge Simulations

A constant pressure boundary condition is programmed at the exit face at a value p_0, and zero capillary pressure is set at both end-faces. For the entry face, another constant pressure boundary condition is set at $p_0 + \rho_i g H$. H equals the length of the core plug; g depends on the rotational speed setting of the centrifuge and ρ_i represents the density of water in imbibition runs and the density of oil in drainage runs. The user will specify the rotational speed in a table indicating speed versus time switch points. g is then calculated within DuMu^x as $g = \omega^2 r$, with $\omega = 2\pi\nu$, ν being the rotational frequency in s^{-1}; and r being the distance to the centre of rotation. Note that r is different for each node. The user needs to supply only the distance of the centre of the plug to the centre of rotation. In the

[1] To the best of our knowledge, the Hassler-type cells that are used in the industry either have circular of spiralling grooves, or "spider web" grooves in the end flanges. This effectively brings about a zero capillary pressure boundary condition.

laboratory, a centrifuge will not immediately spin at the next speed when the setting is changed. This start-up time characteristic can be obtained from the centrifuge manufacturer and needs to be taken into account because at high permeabilities the effect of start-up time is very noticeable. DuMu^x has been programmed to adjust speed as a function of time according to user input. A footbath[2] is simulated by setting S_w=0 at the exit nodes for imbibition runs and S_w=1 for drainage runs as an extension of the boundary conditions.

PP Simulations

The gridding is extended to cover the porous plate with 10 or more grid blocks (dependent on the thickness specified by the user), with a separate refinement scheme similar as discussed above for the core plug proper, i.e. smaller grid blocks near the end-faces. The plate grid blocks are an addition to the core plug gridding, so the number of grid blocks requested by the user for the plug proper is still honoured.

The capillary pressure for the porous plate is derived from a fixed dimensionless table (see Table 1), that is scaled according to the entry pressure given by the user. Also k_{rw} and k_{ro} are fixed for the porous plate itself in terms of Corey functions [16] with parameters as listed in Table 2. Note that a critical oil saturation is used: this represents the percolation threshold for the porous plate and has been fixed at 0.05. The simulation results were found to be not sensitive to the exact value.

Entry and exit boundary conditions are similar to the drainage centrifuge case, except that g is now constant and the entry pressures are set according to a user supplied time table. Output of the simulations is similar to USS.

CI Simulations

Gridding for CI is similar to gridding for PP. The constant injection rate is modeled by programming a constant flux boundary condition at the entry face, similar to the USS set-up. Also similar to USS (or CI for that matter), at the exit a constant pressure boundary condition is programmed. As for CI, the output of the simulations is similar to USS.

VALIDATION OF DUMUX FOR SCAL

We have validated DuMu^x for the simulation of SCAL experiments by a two-step approach. First we compared simulation results against analytical calculations. In this way we obtained a good starting position for the second step in the validation process: comparison with its predecessor MoReS.

Comparison With Analytical Calculations

At zero capillary pressure P_c, the outcome of SS simulations can directly be validated against Darcy's law, after equilibrium is achieved. Pressure drop and saturations were

[2] To prevent back flow and also to better define experimentally the boundary condition at the out-flow face, a so-called footbath may be mounted.

found to duplicate the analytical predictions. After that, we calculated analytically (again with P_c=0), using Buckley-Leverett theory [2], the production behaviour of USS experiments, pressure drop development, water breakthrough and saturation profile development over time. We obtained excellent agreement between theory and DuMu^x simulation results, as shown in Fig. 1 where we compare runs with 50 and 500 grid blocks to the analytical solution for the pressure drop $\Delta P(t)$. We also show that sensitivity was observed to the interpolation of the relperm tables: a good agreement was only obtained with a 20-data-pair table. Finally, we verified multi-speed centrifuge runs at equilibrium levels against the inputted capillary pressure. Single-speed centrifuge simulations were verified against analytical production profiles as predicted by Hagoort's theory [17], with capillary pressure set to zero and the viscosity of the invading phase set to a fraction of 10^{-3} of the viscosity of the displaced phase (in line with Hagoort's assumptions). This proved again that our implementation of gridding and boundary conditions provided a good simulation tool for these simplified cases.

Comparison With MoReS

MoReS results on selected SCAL data sets have been published on the web already many years ago, actually through the SCA web site www.scaweb.org. Three sets of simulation results files are available as a demonstration of USS, SS and centrifuge multi-speed simulations. The sets present production profiles, i.e. flow rates, cumulatives, pressures and differential pressures and average saturation. Separate files for USS and SS also present saturation profiles in the core plug at selected time levels. The files include input data for the individual runs, and all cases have a non-zero capillary pressure.

We have used the same input data as in the three demo sets, and verified for each of these how DuMu^x duplicated the results. Only minor deviations were observed. As an example we present the production profile of the demo multi-speed centrifuge run (Fig. 2). DuMu^x duplicates the results produced by MoReS within 5%. A detailed study was carried out to ensure that the observed differences were not caused by effects hidden in the simulator and that could amplify later in more complicated cases. Again, it was found that a primary source for the deviations was located in the interpolation routines used for the relative permeability and capillary pressure tables. The interpolation used by MoReS, Shell's proprietary simulator, has not been documented in the open literature. For DuMu^x, we employ spline functions with preserved monotonicity, programmed with routines found in the public domain [18], based on an algorithm developed by Fritsch and Carson [19]. Fig. 2 shows the results by DuMux for the standard data set and for a data set where we have populated the tables for k_{rw}, k_{ro} and P_c each with one hundred data-pairs to reduce the effect of interpolation. Clearly, dependent on the saturation range, the production curve for the high-resolution case is shifted up or down with respect to the base case. The deviations are around 3%. It is interesting to note that difference in interpolation can move a production curve with this error margin. Not only does this limit the accuracy that one can hope to achieve in history matching SCAL experiments in general, it also points to an essential range of uncertainty in simulations on the scale of the field.

Finally, we point out that a second reason for the deviations may well be found in the fact that MoReS is working with a finite difference scheme, where variables are calculated at the centre of each grid block, while DuMu^x calculates variables at the nodes that span a grid block, so at the grid block corners.

POROUS PLATE AND CONTINUOUS INJECTION SIMULATIONS

We have employed DuMu^x to study porous plate and continuous injection measurement protocols. Both methods are in use to measure the resistivity index. In addition, the porous plate is in use to prepare samples at initial conditions in an attempt to achieve a more flat saturation profile than generated by the centrifuge technique, while still generating an imbibition capillary pressure curve.

Porous Plate

The porous plate experiment resembles a multi-speed centrifuge experiment in the sense that the pressure at the in-flow end is increased in a step-wise manner and equilibrium has to be established to take a reading for the capillary pressure. Contrary to the centrifuge technique, it is assumed that at equilibrium the in-situ saturation profile is homogenous[3]. Therefore, at equilibrium, the combined pressure drop across the sample and the porous plate at equilibrium is equated to the capillary pressure at that saturation. Moreover, resistivity across the sample is accepted as belonging to that same saturation.

In practice, as with the centrifuge technique, equilibrium is not always achieved. In Fig. 3, we present a typical laboratory measurement of the porous plate technique. Due to operational reasons, the injection pressure was switched to the next step before the production curve flattened out. To study the impact of non-equilibrium, we have simulated this experiment with DuMu^X. In order to obtain a good match between simulations and experiment, we had to shift the capillary pressure at lower S_w considerably (Table 3). In the absence of additional SCAL data, we used assumed relative permeability curves [7]. Both the relative permeabilities and the capillary pressure had to be adjusted to arrive at the match, so the results are only indicative for the sensitivity to the violation of the equilibrium assumption. In any case, the "true" connate water saturation S_{cw} is definitively lower than initially reported from the raw data.

The simulations allow us to "look inside", because the in-situ profiles for saturation and pressure (for the individual phases, as well as for Pc) are printed to file at each time step if so specified. Some general observations:

- Dependent on the shape of the relative permeabilities, a shock front is seen to travel through the core at an early stage of the experiment.
- Later in the experiment, when the mid-saturation range is probed at higher P_c, the saturation distribution remains more flat, when moving from one pressure level to the next.

[3] Note that for an analytical interpretation of the multi-speed centrifuge technique, the Hassler-Brunner [3] correction is applied to account for the saturation distribution.

- At the end of the experiment, high oil saturations may build-up near the out-flow end, because the porous plate keeps blocking oil to leave the plug. The saturation distribution may become quite heterogeneous. Fig. 4 shows a typical case.

From these observations, we conclude that
- Already in the early stages of the experiment, it is important to wait for equilibration. Otherwise, a shock front still moving may distort the saturation profile and both the P_c and the resistivity data are inaccurate.
- When probing the mid-saturation range, equilibration times may be shortened because even transient saturation profiles tend to be flat.
- The build-up of high oil saturations near the out-flow end hampers the flow of water that leaves the core plug through the water-wet porous plate. Therefore, at increasingly higher oil saturations, equilibrium is reached at longer and longer equilibration times.

Continuous Injection

Porous Plate experiments can take typically between 2 to 6 months dependent on K_{abs} and P_c. To accelerate these measurements, Shell has proposed in the 80's a modification: the Continuous Injection method [9]. The CI protocol requires injection at constant rate rather than at constant pressure. The rate is chosen in the order of 1 MOV (Movable Oil Volume) in two weeks. As with the PP method, a porous plate is mounted in direct contact with the core plug at the exit. The original aim was to accelerate resistivity index measurements for water-wet samples. However, in the case that capillary forces dominate viscous forces, the pressure drop across the plug will approximate the capillary pressure and can be determined as a function of saturation as the experiment progresses. As was the case for PP, for the resistivity measurements to be valid, it is necessary that the saturation profile is reasonably flat in the core plug. In other words: it is implicitly assumed in CI that capillary forces stretch the saturation profile into a flat profile. However, contrary to PP, viscous forces will be present and the measurement is essentially dynamic. Certainly at high oil saturations, oil may build up against the porous plate like in PP experiments. So, an assurance is needed that the saturation profile is reasonably flat during the measurements. Simulations of the experiments will be useful in the design of a particular CI protocol for an individual plug.

Fig. 5 shows the differential pressure for a synthetic data set for a typical water wet case, as a function of the average saturation, predicted by $DuMu^x$. Three different injection rates were chosen, roughly one order of magnitude slower in each case. The plot also shows the actual capillary pressure curve used as input. At the highest rate, viscous forces dominate capillary forces already early in the experiment, and even the plateau value is affected. For the slowest rate, the pressure differential approximates the true capillary curve quite well, but the apparent S_{cw} is still significantly higher than the true S_{cw}. Simulations of the experiment are necessary to aid in the interpretation of the differential pressure as a capillary pressure measurement.

Fig. 6 shows the calculated resistivity curve, together with the inputted resistivity curve, for the same speeds as used in the numerical experiment of Fig. 5. The rate effect is significant: at high speed the curve is strongly curved, while the underlying saturation exponent has just a constant value of 2. This shows the power of simulating CI experiments: a wrong design for a measurement may result in data biased by a heterogeneous saturation distribution. For an analytical analysis of this phenomenon, we refer to [20].

CONCLUSIONS

- SCAL simulations are sensitive to the type of table interpolation technique used for relative permeabilities and capillary pressures. We recommend that full scale reservoir simulations be tested for the impact on project performance of this phenomenon.
- The measurement of water and oil relative permeabilities in drainage mode will assist in optimising a Porous Plate measurement protocol for specific flow units reducing measurement time as well as improving measurement accuracy of P_c and resistivity.
- Capillary pressure measured with the Porous Plate method, without interpretation-by-simulation is likely to give too high values for S_{cw} and correspondingly too high Pc at lower water saturations in general.
- The Porous Plate method does not necessarily provide a flat saturation profile at low initial water saturation.
- Although the Continuous Injection method originally was not designed to provide Pc data, a limited part of the Pc curve is accessible.
- Resistivity measurements with the CI method are sensitive to the injection rate. Simulations can be used to design the experiment.
- There is a risk that resistivity measurements with the Continuous Injection method access a saturation range that is smaller than can be obtained with the Porous Plate method. Simulations can be used to optimise the protocol.

DuMu^x through our user interface SCORES is available at www.jgmaas.com/scores. In line with the philosophy of GPL(2), simulations are provided free of charge. A password can be requested through the web site. Each experimental SCAL protocol is addressed by an individual web page with a common look and feel. Additional information is provided through links on the various web pages.

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Table 1. Dimensionless capillary pressure used for the porous plate in the PP and CI simulations. Pc is scaled according to user defined entry-pressure.

S_w	0.	.1	.15	.18	.20	.75	.80	.90	.97	.98	.99	1.
$P_{c\ plate}$	10^3	10^2	20	2	1.5	1.2	1.1	1.01	1.	.3	.1	0.

Table 2. Water-wet Corey parameters used for the drainage water and oil relative permeabilities for the porous plate in the PP and CI simulations. Note that for drainage, Sor in the Corey formulation[4] for the water relative permeability is set to zero, while for the oil relative permeability a critical oil saturation is set to account for the percolation threshold.

	S_{cw}	S_{or}	n	$k_{r\ endpoint}$
k_{rw}	0.05	0.	5	1.
k_{ro}	0.05	0.05	2	.7

Table 3. Original P_c and adjusted P_c for an actual Porous Plate experiment. Note that the history match of the measurements indicated that the lowest two saturations needed to be reduced. This effectively lowers the P_c at low water saturation and is to be expected when equilibrium was not achieved in the PP experiment.

P_c (bar)	12.41	5.52	2.77	1.72	.97	.55	.28	.14	.07	0.
S_w orig	.195	.419	.641	.833	.915	.963	.971	.975	.982	1.
S_w adj	.1	.35	.641	.833	.915	.963	.971	.975	.982	1.

[4] We use as Corey formulation [16] for phase i: $k_{ri}(S_i) = k_{r\_endpoint} * ((S-S_{ic})/(1.-S_{cw}-S_{or}))^{n}$

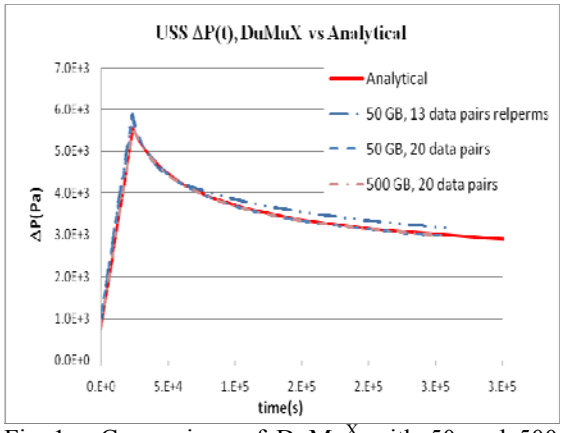

Fig. 1 Comparison of DuMu^X with 50 and 500 grid blocks vs analytical for an USS experiment. With 13 data pairs relperm tables a deviation is observed.

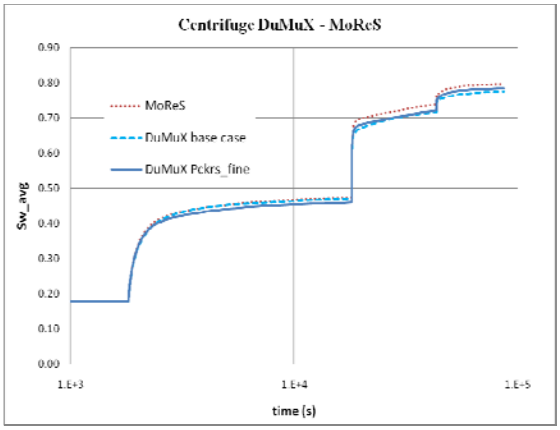

Fig. 2 Validation of DuMu^x simulations against MoReS for the centrifuge demo data set. Effect of densely spaced table interpolation.

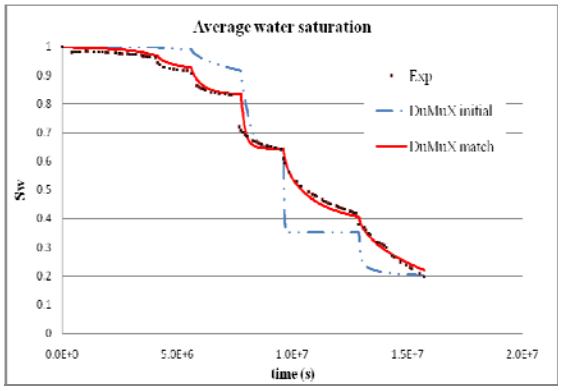

Fig. 3 Match of Porous Plate laboratory data. Curvature is dominated by k_r's; levels are dominated by P_c table.

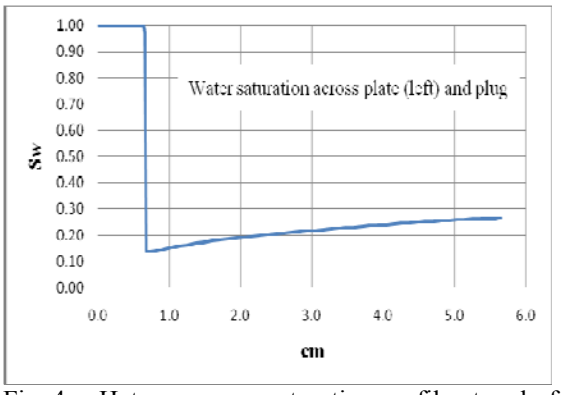

Fig. 4 Heterogeneous saturation profile at end of the experiment shown in Fig. 3.

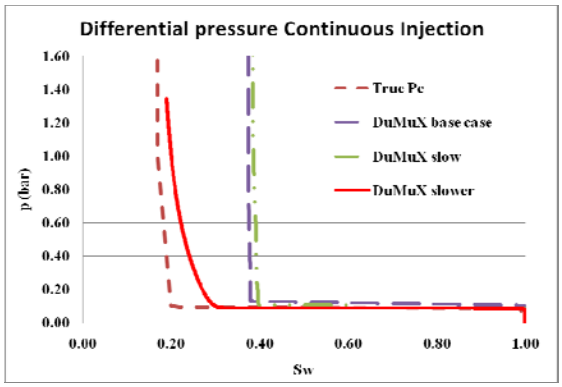

Fig. 5 Continuous Injection. Synthetic case, rate dependency of differential pressure.

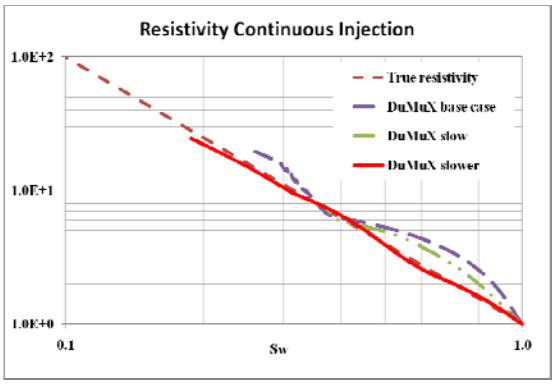

Fig. 6 Continuous Injection. Synthetic case, rate dependency resistivity measurement.