SCA-9719

Computer simulation of Special Core Analysis (SCAL) flow experiments shared on the Internet

J.G. Maas and A.M. Schulte

Shell International Exploration and Production B.V., Research and Technical Services, P.O. Box 60,
2280 AB Rijswijk, The Netherlands

Abstract

Measurement artefacts due to the interference of relative permeability and capillary pressure (as will occur in any SCAL flow measurement) may lead to residual oil saturations that are 10 saturation units higher than the true residual oil saturation. Simulations of the experiments have proved to be an excellent tool to unravel that interference. Also, simulation of SCAL flow experiments has been very successful for a reconciliation of seemingly contradicting results that may come out of different flow experiments on the same core plug. Therefore, there is significant business value in interpretation by simulation.

The simulation technology as applied on the scale of oil and gas reservoirs is well advanced, but the application of simulations on the scale of the core plug is still relatively immature. SIEP - RTS is investigating how Shell developed SCAL simulation technology could be shared with the industry, as a contribution to the advancement of SCAL measurement technology.

This paper will discuss in detail the capabilities of a full-fledged SCAL flow simulator that, as a pilot test, has been made available through WWW pages on the Internet. The simulations are provided free of charge.

The three major experimental techniques, i.e. the UnSteady State (or Welge) technique, the Steady-State and the Centrifuge technique, are handled with one common "look and feel". The WWW interface has been designed to require a minimum of user input and to provide a detailed report of the evolution in time of water and oil production, pressure drop and saturation profile. The results of the simulation are E-mailed back to the user in the form of a spreadsheet.

1. Introduction

A long standing issue in the measurement of relative permeability on core plugs is the interference by the capillary pressure: the so-called capillary end-effect. The effect is probably best known in the preparation of water-wet core plugs at connate water saturation. The primary drainage capillary pressure curve causes a water end-effect: near the outflow end of the plug, water is retained under a balance of viscous and capillary forces. With the increased understanding over the last years that most oil reservoirs are probably mixed-wet rather than water-wet, it became necessary to account for an oil end-effect during the measurement of the imbibition[1] relative permeabilities at lower oil saturations.

The basis of the problem lies in the fact that the standard analytical techniques used to extract relative permeabilities from UnSteady-State (USS), Steady-State (SS) or from centrifuge experiments assume a zero capillary pressure. By neglecting a capillary end-effect, the extracted relative permeability curve of the displaced phase will drop-off too fast: the mobility reduction due to capillary hold-up will be interpreted as a relative permeability reduction.

In the industry, various approaches have been developed to either design the flow experiments such as to minimise the impact of the capillary end-effect (e.g. by extending the core plug by an "end-piece", or by increasing the flow rate) during the experiment, or by correcting the results from the experiment afterwards, during the interpretation phase, by a mathematical procedure. A combination of both an optimal design and a correcting interpretation technique is expected to produce the best results. The reliability of the end product depends on the size of the capillary pressure and on the accuracy with which the capillary pressure is known beforehand.

In the measurement of the capillary pressure, particularly close to end-point saturations, a (low) relative permeability will cause a time-delay in obtaining pressure equilibrium. Similar approaches as described for relative permeability measurements are available to account for the interference by relative permeability in capillary pressure measurements.

In effect, we have a vicious circle in the determination of relative permeability and capillary pressure of a core plug. An elegant way out is interpretation by simulation. Consistency of the data is ensured by history matching two experiments simultaneously, with one single data set for relative permeabilities and capillary pressure. One experiment designed to measure relative permeability, and another, on the same plug or on a twin plug, to measure capillary pressure. The interference can then be made visible and the uncertainty in the resulting data is quantifiable.

In addition, the impact of interpretation by simulation can be significant, when truly different results are obtained. As discussed in earlier work [1], in a number of cases, scope for a lower residual oil saturation proved to be 10% in saturation or more. Still, this technology is not routinely available from third party SCAL laboratories. SIEP - RTS is investigating how Shell developed SCAL simulation technology could be shared with the industry, as a contribution to the advancement of SCAL measurement technology. As a pilot test, the authors have constructed a WWW user interface for a Shell SCAL flow simulator at http://www.sieppartners.shell.com/scores. SCORES stands for Special CORE analysis Simulator. The simulations are provided free of charge.

This paper will discuss in detail the capabilities of the simulator. First, we address the general principles. Subsequently, details are presented on the simulator set-up for the USS, the SS and the centrifuge method. Further, we discuss issues in interpretation by simulation of SCAL flow experiments and present conclusions.

---

[1] In this paper, we will use "imbibition" for increasing water saturations, and "drainage" for decreasing water saturations, irrespective of wettability.

2. Simulation of flow experiments

The numerical simulation of flow of fluids though porous rock has been discussed at any sort of detail in numerous text books [2] and a detailed discussion is beyond the scope of this paper. SCORES is based on MoReS, the Shell Group reservoir simulator. MoReS is a fully implicit, 3-D, (fractured) reservoir simulator for compressible, multi component, multi-phase flow. MoReS handles compaction, chemical reactions, phase equilibria, and has many other special features (e.g. non-Darcy flow, capillary number dependent relative permeability, a flexible and programmable input language). Extensive well-control options and a surface network description also have been included [3].

Only a limited sub-set of MoReS capabilities is required to simulate with a reasonable accuracy the flow of water and oil in standard laboratory experiments. If during the pilot phase, it appears that SCORES functionality falls short of what is required, it may be easily extended. At this moment SCORES has the following limitations: 1-D; homogeneous rock; no compaction; incompressible and immiscible fluids; water - "black oil"; isothermal; capillary number independent relative permeabilities; output of a small number of parameters (specified in the following Sections).

In short, we have attempted to provide only the functionality that is required in day-to-day SCAL flow experiments, not a research tool. In that way, also the input requirements of SCORES could be minimised, increasing significantly its accessibility for SCAL laboratory experimentalists unfamiliar with simulation technology.

In the next Sections, we will discuss in detail how the USS, SS and centrifuge experiments have been implemented in SCORES.

2.1 The UnSteady-State experiment

In the standard USS experiment, water is injected at constant rate into the oil filled core plug, prepared at (usually) connate water. Initially, only oil will be produced. After water breakthrough, the oil production rate will decline rapidly. The experiment is halted when oil production cannot be observed anymore. From the water and oil production rates after breakthrough, together with a measurement of the pressure drop across the sample, the relative permeabilities are extracted with the well-know JBN [4] analytical method.

Modelling

The experiment has been modelled as follows. We have subdivided the core plug into N grid blocks. All grid blocks have the same dimensions into the x and y direction, that are perpendicular to the direction of flow into the z direction. Most grid blocks have the same thickness Δz, but to be able to keep track of capillary effects near the inflow and outflow ends, we have reduced the size of the first four and last four grid blocks as follows:

grid block Nb	1	2	3	4	5	...
grid block Nb	N	N-1	N-2	N-3	N-4	...
size	$.1\Delta z$	$.2\Delta z$	$.4\Delta z$	$.8\Delta z$	Δz	Δz

SCORES adds two more grid blocks, one at each end of the plug, to accommodate the inflow and outflow tubes (the "surrounding" grid blocks).

The user specifies N on the WWW page, from a small selection menu. The default is N = 50. Subsequently, the user specifies the length L and the area of the plug. SCORES will calculate Δz from L and N.

The WWW page asks for porosity and absolute permeability, one value for each, valid for the whole plug. This is in line with the assumption of homogeneity that is at the basis of the JBN method. SCORES assigns these properties to each grid block. Also the relative permeability and capillary pressure tables given through the WWW page are assigned to each block.

Entrance and exit blocks

In the actual experiment, usually an entrance and an exit chamber are cut into the flanges that close the core holder. Therefore, internal to SCORES, for the 2 "surrounding" grid blocks, the absolute permeability is set to 10^4 times the plug permeability. The porosity of these 2 blocks is set to unity. SCORES requires the same type of data for each grid block, and makes no exception for the two surrounding blocks. Consequently, also relative permeability and capillary pressure tables are required for these blocks. There is no consensus in the literature on how to model boundary conditions for SCAL flow experiments. As mentioned above, SCORES is not meant as a research tool and therefore only one option has been made available: the capillary pressure of the two surrounding blocks is set to zero and the relative permeabilities are set linear, with an end-point of unity.

In the entrance block, an injection node is defined that injects water at the rate prescribed by the user. A production node is defined in the exit block. Internal to SCORES, all input for these nodes is generated that has no direct relevance for an experimentalist.

Fluid properties

As mentioned above, only water and oil can be present in the model and have been defined as incompressible fluids. The WWW page asks for viscosities and densities. The densities play a role only if the experiment is oriented vertically.

The WWW page asks for a value of the interfacial tension between oil and water. This value is used only when the Leverett-J option has been activated on the WWW page. In that case, the table typed in the capillary pressure location will be read as a dimensionless J-function dependent on water saturation. SCORES will calculate the capillary pressure, to be used in the grid blocks of the core plug as follows:

$$p_c(S_w) = s\sqrt{\frac{j}{K}}J(S_w) \qquad (1)$$

(For an explanation of symbols, see the nomenclature at the end of this paper.)

Flow rate Table

To reduce or to verify the size of the capillary end-effect, the flow rate is often increased at the end of the experiment. For that reason, the WWW page accepts a time table to specify injection rate at several times.

Simulator control data

To allow some tuning, a minimum amount of data can be used to control the simulator time stepping. A start time step and a maximum allowable time step can be set and a maximum allowable saturation change per time step. Default values have been provided that should be appropriate in most cases. If in doubt, the values for these parameters can be reduced to increase simulation accuracy. However, very small values may increase numerical diffusion [2].

Output

SCORES will simulate the experiment, based on the input specified on the WWW page. The output is presented in tabular form, as a generic spreadsheet. Columns are separated by tabs. Most spreadsheets will recognise this format and import the data without any conversion. For the USS, SCORES produces two spreadsheets that are E-mailed back to the user. The first spreadsheet contains an echo of all input data, followed by a table that shows, for each time step: time step number; time; average water saturation in the plug; the phase pressures in the first and last grid block in the plug; the phase pressure drop across the plug; the water injection rate; the water and oil production rates and cumulatives.

The second spreadsheet shows a tabulation of the saturation of each grid block in the plug, i.e. a saturation profile, for each time specified in the flow rate table. The user can specify the same flow rate at different times to signal to SCORES that saturation profiles need to be generated at a sequence of times within the same flow period.

2.2 The Steady-state experiment

In the SS experiment, water and oil are injected at varying ratios into the oil filled core plug, prepared at (usually) connate water. The total flow rate is kept constant. At each water/oil ratio, a stabilisation period needs to be honoured, to achieve the steady-state: a constant saturation profile in the plug and a constant pressure drop over the plug. At steady-state, the relative permeabilities can be extracted in a straightforward manner from:

$$\vec{q}_i = -K\left(\frac{k_{ri}}{m_i}\right)\vec{\nabla} p_i A \qquad (2)$$

Modelling

The modelling of the SS experiment is nearly identical to the modelling of the USS experiment described above. We will only highlight the differences here.

Fractional flow time table

The flow rate table for the USS has been replaced by a fractional flow time table. At a sequence of different times, the fractional flow of water f_W should be specified. At present, the total flow rate in SCORES cannot be varied over the duration of the experiment.

Output

In the output spreadsheet, the total liquid injection rate and total cumulative injected liquid are listed. The echo of the input shows at what times the water/oil ratio was changed. The layout of the second spreadsheet is identical to the layout of the second spreadsheet of the USS experiment. In this case, the saturation profiles in the plug are shown for the times listed in the fractional flow time table. By specifying the same fractional flow for a sequence of times, the development of the saturation profile towards the steady state can be monitored.

2.3 The centrifuge experiment

Two different modes exist: imbibition and drainage, for two different types of measurements. The multi-speed experiment is used for the measurement of the capillary pressure curve, the single-speed experiment is used for the measurement of the relative permeability of the expelled phase. This method is particularly apt to determine this relative permeability close to the end points of the saturation range, i.e. S_{cw} for drainage and S_{or} for imbibition runs. Although the relative permeability of the *invading* phase will have an impact on the production profile, it cannot be determined in the centrifuge with a reasonable accuracy.

During centrifugation, the cumulative production of the expelled phase is monitored in the collection tube through a stroboscopic system. The multi-speed and single-speed experiment each have their own analytical procedures for data extraction. The Hassler-Brunner method [5] is employed to extract the capillary pressure from the production profile of the multi-speed experiment. Corrections can be applied to account for non-uniform gravity in the plug [6]. Hagoort's method is employed to extract the relative permeability of the expelled phase for a single-speed run [7].

Modelling

The grid block arrangement for modelling of the centrifuge experiment deviates significantly from the USS and SS arrangements. Details are shown in Fig. 1. The upper and four lower grid blocks do not belong to the plug: the upper block (Δz = 1 cm) represents the surroundings at the inflow face, the two small lower blocks (with Δz equal to Δz in the plug) represent the surroundings at the outflow end.

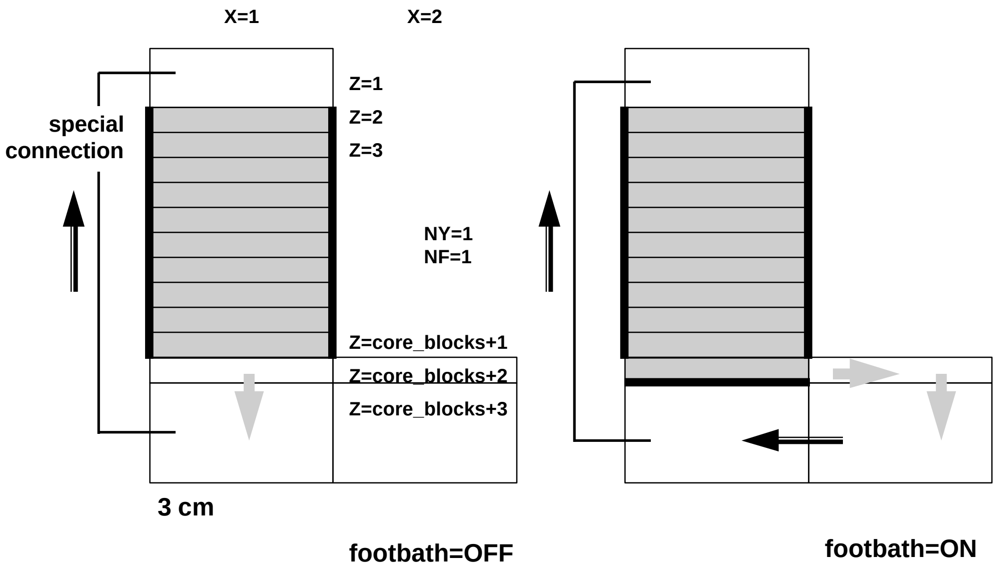

Fig. 1 grid block geometry for the simulation of the centrifuge experiment

The two large lower blocks ($\Delta z = L$) represent the collection tube. The saturation of the latter increases during production, whilst the saturations of the smaller outer blocks remain constant throughout the simulation. The permeability of all blocks outside the plug is set to 10^4 times the plug permeability and the porosity is set to unity. Also, linear relative permeabilities and a zero capillary pressure are assigned to these blocks.

A so-called special connection is included to permit flow of fluid displaced from the collection tube back to the other end of the plug, as indeed occurs in the real experiment. We could have modelled this flow route with ordinary grid blocks, but MoReS technology allows for such (literally) shortcuts, which simplifies the internal input generation and equations to be solved. In addition, numerical robustness is increased. The transmissibility of the special connection is set to 10^4 times the transmissibility between the core blocks.

As indicated, a footbath can be activated. If "footbath" is set to "On" on the WWW page, the footbath is included in the model by (Fig. 1):

- setting the vertical transmissibility between the lower two blocks just below the plug to zero
- setting the horizontal transmissibility between the two small lower blocks to 10^4 times the transmissibility between core blocks
- setting the initial saturation of the block just below the plug to 100% water in drainage mode (while the surrounding phase is oil) and to 100% oil in imbibition mode (while the surrounding phase is water).

With the footbath activated, flow of the expelled phase is as indicated at the right of Fig. 1. Inflow of surrounding phase through the outlet, counter-current to the expelled phase, is disabled.

It is of interest to note that the same grid block arrangement is used for imbibition and for drainage. SCORES just switches the sign of the gravity in the simulation. For drainage, gravity points towards the collection tube; for imbibition, gravity points away from the collection tube.

RPM time table

The centrifuge WWW page shows a RPM time table. The user may specify the speed settings at various times. SCORES will calculate the value for gravity in each grid block according to:

$$g = w^2 r = (2pRPM / 60)^2 r \qquad (3)$$

A single-speed run to determine relative permeability will just need one entry in the table.

A centrifuge requires a certain start-up time to reach a pre-set RPM. Particularly for plugs with a high absolute permeability (say Darcy range), this delay in achieving the required speed will affect the production profile. SCORES takes account of that through the data provided by the user on the WWW page. The user should consult the manufacturer of the centrifuge for these data.

Simulator control data

Compared to the USS and SS WWW pages, the centrifuge has one additional entry: the maximum scale-up factor for time stepping. If saturations change only very slowly, a time step size will be multiplied by this factor to set the next time step size. Since centrifuge experiments typically take much longer than USS or SS experiments, this factor may help to reduce the simulation effort. A reasonable default value has been supplied.

Output

Only one spreadsheet is produced for the centrifuge experiment. Current centrifuges do not allow for the measurement of the saturation profile. If it turns out that there is a requirement for plotting the saturation profiles, SCORES can easily be updated.

The current spreadsheet contains an echo of all inputted data, followed by a table that shows, for each time step: time step number; time; average water saturation in the plug; water saturation at the top (= inflow face) and at the bottom (= outflow end) of the plug; cumulative oil and water collected in the tube. Note that during drainage, the water saturation in the tube will increase, and the oil is displaced out of the collection tube (through the special connection, back to the other side of the plug). Therefore, the cumulative oil production will be listed as negative during drainage. For imbibition, the water production will be negative.

3. Discussion

When running simulations of SCAL flow experiments, a number of issues arise.

Number of grid blocks

The default number of grid blocks N in SCORES runs is set at 50, but may be increased by the user. A larger number of grid blocks will increase simulation accuracy, particularly when a moving saturation front needs to be tracked in the plug. Numerical dispersion will "smear-out" any steep saturation fronts. A rough estimate is that the relative spread of a front reduces as $1/\sqrt{N}$, as N increases. The penalty is in the increase in calculation effort per time step and in the increase in number of time steps. The increase in number of time steps is somewhat less obvious than the increase in effort per time step. The reason for the increase in number of time step is that the maximum allowable change in saturation in each grid block is not changed, when the number of grid blocks is increased. As long as a saturation front moves through the plug, each grid block in turn will undergo a large saturation change, subdivided over several time steps.

In standard SCAL flow experiments, saturation fronts do not need to be tracked through the sample and a total of 50 grid blocks is sufficient to describe the slowly changing saturation levels in a plug.

Initial saturations

The WWW pages ask for an initial water saturation S_{wi}. This saturation is then assigned to all grid blocks in the plug. It must be stressed that S_{wi} cannot be chosen freely: in practice, due to the experimental (re)arrangements after the preparation at low water saturation, it is unlikely that the plug is far from $p_c = 0$. Therefore, there is a link between the range of water saturations within which S_{wi} can be set, and the (shape) of the capillary pressure curve. To ensure initialisation that is physically sound, SCORES will test p_c at S_{wi}. When this value is far from zero, the data are not accepted. Again: SCORES is meant as a practical tool, not as a research tool.

Initial water saturations in surrounding grid blocks are treated separately in SCORES. For USS, the surrounding grid block at the injection face is always initialised at 100% water, while the surrounding grid block at the production end is initialised at 100% oil. We believe that this initialisation is closest to the practical situation in an USS experiment at start up. For the same reason the surrounding grid blocks both are set initially at 100% oil for SS.

The situation in centrifuge experiments is more complicated and has been discussed in detail already in the previous Section.

No Corey description in SCORES

Although a Corey description of relative permeabilities is quite common throughout the industry, we have opted not to include it in SCORES. The relative permeabilities that are used as input for SCORES are extracted from laboratory experiments. Current techniques result in a point by point description of the relative permeability curves, not in a Corey formulation. In addition, however convenient and logical the Corey description is, there does not seem to be a sound physical basis for this description. We feel that to arrive at a consistent data set, as discussed in Chapter 1, the relative permeabilities should not be straight-jacketed into a Corey formulation.

Limits in SCORES

All parameters on the WWW pages have been limited in range, either explicitly by showing a small menu, e.g. for the number of grid blocks, or by sanity checks that are carried out on the data when the user submits the WWW form. For example, S_{wi} must be between S_{cw} and $1\text{-}S_{or}$. We have aimed at protecting the user from inputting unrealistic data, that would only waste the time of the person analysing the E-mailed results. We believe that all restrictions are helpful rather than that these hold the user back. In the case that the limits interfere with useful work, please contact the authors through the E-mail address indicated on the WWW page.

History matching SCAL flow experiments

We will show here some important pitfalls that exist in this area, to clarify what the significance is of a match between experimental production behaviour and simulation. For each of the experimental techniques, we will discuss the "trivial" match, vis à vis the match that truly brings about a better interpretation of the experiment and therefore a more reliable data set on relative permeabilities and capillary pressure. However, also the "trivial" match has value, as will be demonstrated below.

In the case of an USS experiment, it should be realised that the "raw" relative permeabilities that are extracted by the analytical JBN method, implicitly require $p_c = 0$. In reality, p_c will not be zero, particularly not when the saturation is close to either S_{cw} or $1\text{-}S_{or}$. However, when these raw permeabilities are fed into a simulator, *together with* p_c *set equal to zero*, the simulation results should match perfectly with the experimental results for water and oil production and pressure drop. This is what we call the trivial match. In this way, a consistency check can be carried out on the analytically derived data and/or on the quality of the simulation.

Of course, an experimentally determined in-situ saturation profile will reflect the presence of a non-zero capillary pressure and therefore will *not* match with the profile generated by the simulator. In effect, the trivial match was on incomplete data. It is our experience that to extend the matching to the saturation profile is extremely difficult and that the interference of relative permeabilities and capillary pressure cannot be unravelled through simulation[2]. A separate experiment, to measure capillary pressure (and accounting for relative permeabilities) would be required for the simulation-and-match approach to work.

The situation for SS is somewhat more complicated. The raw relative permeability data, analytically extracted from the experiment, should produce a match in the simulated pressure profile at the end of each fractional flow period (the steady-state), again using p_c equal to zero, as in the USS case. However, the transient part of the pressure profile will usually not match. For the same reasons as with the USS, the saturation profiles in the plug also will not match with these "raw data" simulations. Again, a separate experiment to measure capillary pressure would be required to resolve the matching by simulations.

For centrifuge experiments, the situation is different again. When simulating a multi-speed run, the production levels at the end of each period should match when favourable (i.e. high mobility) relative permeabilities are input together with the Hassler-Brunner extracted capillary pressure curve. The shape in the transient periods is governed often by relative permeabilities and therefore will not match using the raw data.

For a single-speed run, the production profile should match perfectly when the capillary pressure is set to zero (in line with Hagoort's assumptions) and when the relative permeability of the invading phase is set to very favourable mobility. As with the USS, the true capillary pressure is not equal to zero and such simulations are only a, very useful, sanity check. The single-speed run is particularly useful to determine the "tail-end" of the relative permeability of the expelled phase at low saturation. In that respect, this technique is a good extension of an USS or SS experiment, that are most reliable in the mid-saturation range.

---

[2] It is of interest to note, that it has been demonstrated in literature [8] that capillary pressure can be extracted from saturation profiles measured during flow experiments for relative permeability measurements. The technique reported in Ref. 8 employs a direct data reduction, without reverting to simulations.

In view of the above, we recommend to design a combination approach, if the expected business impact permits, using an (U)SS experiment, combined with a single-speed centrifuge run for relative permeabilities; together with a multi-speed run for capillary pressure. In that case, three experiments need to be matched by simulations with a single data set for relative permeability and capillary pressure. The iterative matching effort may be tedious, but in our experience, a truly new quality of data is often achieved. As mentioned above, in particular the residual oil saturation derived by history matching can be significantly lower than as inferred from the raw analytical data [1].

4. Conclusions

A detailed description has been presented of the modelling of SCAL flow experiments with SCORES, a limited version of the Shell Group reservoir simulator MoReS. SCORES is available through WWW pages on the Internet. The details presented here should be sufficient to show the way for adapting flow simulators for use in the interpretation of SCAL flow experiments.

To resolve the interference between relative permeabilities and capillary pressure in any SCAL flow experiment, numerical simulations may be used. History matching with one single data set of relative permeabilities and capillary pressure of a (U)SS and a multi-speed centrifuge run should result in a consistent data set, properly characterising flow at the scale of the core plug.

To cover the full saturation range of interest, down to low oil saturations, an (U)SS experiment and a multi-speed centrifuge run should be amended with a single-speed centrifuge run. In that case, the simulations should match three experiments at once, before consistency can be assumed.

5. Acknowledgements

The authors thank the management of Shell International Exploration and Production B.V. (SIEP) for permission to publish this paper.

6. Nomenclature

A	m^2	area
g	m/s^2	acceleration
J	-	dimensionless Leverett J function
K	m^2	absolute permeability
k_r	-	relative permeability
L	m	plug length
N	-	number of grid blocks
p	Pa	phase pressure
q	m^3/s	flow rate
RPM	1/min	rotations per minute
r	m	radius to centre of grid block
S	-	saturation

z	m	location of grid block in the flow direction
Δ		difference operator
μ	Pa.s	viscosity
σ	N.m	interfacial tension
φ	-	porosity
ω	s^{-1}	circular frequency
∇		gradient

Subscripts

c	capillary
i	phase i
cw	connate water
or	residual oil
w	water
wi	water at initial conditions

References

[1] Kokkedee, J.A., Boom, W., Frens, A.M. and Maas, J.G. "Improved Special Core Analysis: Scope for a reduced residual oil saturation", SCA9601 presented at the Intl. SCA Symp. in Montpellier, September 1996.

[2] See for example: Aziz, K. and Satari, A., *Petroleum Reservoir Simulation*, Applied Science Publishers Ltd, London, 1979.

[3] Regtien, J.M.M., Por, G.J.A., van Stiphout, M.T. and van der Vlugt, F.F., "Interactive Reservoir Simulation", SPE 29146, 1995.

[4] Johnson, E.F., Bossler, D.P. and Neumann, V.O., "Calculation of relative permeability from displacement experiments", *Trans. AIME*, (1959), **216**.

[5] Hassler, G.L., and Brunner, E., "Measurement of capillary pressure in small core samples", *Trans. AIME*, (1945), **160**.

[6] Fleury, M. and Forbes, P., "Radial effect and sample heterogeneity effect on centrifuge capillary pressure curves", SCA9534 presented at the Intl. SCA Symp. in San Francisco, September 1995.

[7] Hagoort, J., "Oil recovery by gravity drainage", SPE 7424, 1980

[8] Nordtvedt, J.E., Ebeltoft, E., Iversen, J.E., Sylte, A., Urkedal, H., Vatne K.O. and Watson, A.T., "Determination of three-phase relative permeabilities from displacement experiments", SPE 36683, 1996, and references therein.