GAS-LIQUID RELATIVE PERMEABILITIES FROM ONE-STEP AND MULTI-STEP CENTRIFUGE EXPERIMENTS

F. Bauget[1], S. Gautier[2], R. Lenormand[1], A. Samouillet[2]
[1]Cydarex, [2]IFPEN

ABSTRACT

This paper presents the advantages and limitations of deriving relative permeabilities from centrifuge experiments. We first recall the theoretical background for capillary pressure and relative permeability determinations from centrifuge experiments.

The experimental set-up for the monitoring of fluid production is then described. The originality of the IFPEN system is the capacitance measurement that gives a better accuracy than the video system.

For mono-speed experiment, the standard Hagoort K_r calculation is compared to history matching with and without capillary pressure. Domains of validity of this method are presented as function of fluid viscosities and capillary pressure.

For multi-speed experiments, the main advantage is to have a simultaneous determination of both P_c and K_r on the same experiment. In this paper we also discussed the limitations of the standard Forbes method based on a finite difference. More accuracy is obtained by fitting the experimental P_c curve and applying the Forbes method on the continuous curve rather than on the experimental points only.

The main conclusions of our study are: 1) for multi-step experiments, the standard discrete method proposed by Forbes is not accurate enough. More accuracy is obtained by fitting the experimental P_c curve and applying the Forbes method on the continuous curve rather than on the experimental points only; 2) the K_r determination using a mono-speed experiment can be improved by using numerical history matching taking into account the recorded rotational speed and a P_c curve derived from mercury injection on a companion plug or end-trims; 3) Although a mono-speed experiment takes few hours and a multi-step experiment few days, multi-speed can often be considered since it gives both Kr and Pc curves.

INTRODUCTION

Centrifuge experiments are used to calculate relative permeabilities and capillary pressure. Compared to standard gas injection advantages of this technique are numerous:

- Centrifuge displacement is not subject to fingering instabilities induced by local heterogeneities.
- High capillary pressures can be obtained on short sample, 2.5 cm for this study, that is not possible in standard gas injection.
- Centrifuge method is fast and 4 (or 6) samples can be operated at the same time.

However, the Kr determination by centrifuge is mainly limited to gas/liquid systems, at least for single speed experiment associated with analytical interpretations.

For a multi-speed experiment, the Kr determination needs history matching with a numerical simulator, but this optimisation is also required for Kr determination by steady-state or unsteady-state method. However, from our experience, history matching with centrifuge is more difficult than for a displacement since there is only one curve to fit.

The purpose of this paper is to discuss the best method to obtain a relative permeability from a gas/liquid centrifuge experiment. We will recall the principle of single and multi-speed methods, present and discuss the experimental results. The main conclusion is that mono-speed interpretations can be improved by using history matching with the recorded centrifuge speed and a P_c curve derived from mercury injection.

BACKGROUND

Flow equations

In gravity displacement the flow is controlled by the densities difference. The local velocity for each fluid is given by the generalized Darcy's law:

$$u = -\frac{K \, K_r}{\mu}\left(\frac{\partial p}{\partial x} - F\right) \qquad (1)$$

with $F = \rho g$ the potential, g being the gravitational acceleration, ρ the fluid density, K the permeability, K_r the fluid relative permeability, μ the fluid viscosity, p the fluid pressure and x the distance along the sample. For a centrifuge experiment the potential is centrifugal: $F = \rho \omega^2 r$, where r is the distance from the centrifuge axis and ω is the rotational speed.

In a centrifuge experiment, the sample is completely immersed in one fluid. The general boundary conditions are two free surfaces at both ends and spontaneous displacement should be considered at both ends. However, spontaneous displacements are generally performed (and measured) before the experiment and the mathematical models do not allow further countercurrent flow at the outlet (this point can be controversial).

At a given rotational speed and equilibrium, the capillary pressure at the entrance is expressed as follows:

$$P_c = \left(\rho_w - \rho_g\right)\frac{\omega^2}{2}\left(r_{max}^2 - r_{min}^2\right) \qquad (2)$$

with ρ_g and ρ_w the gas and water densities, r_{max} and r_{min} the maximum and minimum distance from the centrifuge axis. For a detailed review see for example reference [1].

There are several types of centrifuge experiments: single-speed, multi-speed, constantly-accelerating [2] and constant flow rate centrifuge technique [3]. We will restrict this paper to the two main techniques: single speed and multi-speed. A single speed experiment is performed at a unique and constant rotational speed and is mainly used to calculate the relative permeability of the displaced fluid using an approximate analytical method [4]. The multi-speed experiment, performed with successive increasing steps of constant rotational speed, is mainly used to determine the capillary pressure [5, references

in 6]. It also allows simultaneous determination of the relative permeabilities and the capillary pressure by history matching [7, 8, 9].

Single-speed experiment, the Hagoort method to calculate relative permeability [4]
The main advantages of this method are: the experiment is short in time, the calculation is analytic, and there is no need of any capillary pressure knowledge.
The Hagoort method is an analytical calculation of the oil relative permeability from a single speed oil-gas drainage experiment. The idea is to interpret the centrifuge experiment as a gravity drainage using the following major assumptions: capillary effects are negligible, the invading fluid mobility is much larger than the displaced fluid mobility, the acceleration along the sample is uniform. This leads to two equations giving the displaced fluid relative permeability and the saturation from the production curve:

$$N_p = 1 - S^* + K_r(S^*)t_D$$
$$K_r(S^*) = \frac{dN_p}{dt_D} \tag{3}$$

Where S^* is the reduced saturation of the displaced fluid, N_p is the cumulative production as fraction of movable volume, and t_D is a dimensionless time. Because the centrifuge experiment has to be compared to gravity drainage flow regime at pore scale must be similar, i.e. capillary controlled. Therefore Hagoort stated that Bond number should not exceed 10^{-3} when for a gravity drainage this number is of the order of 10^{-5}. The Bond number is defined as $N_b = (\Delta\rho K\omega^2 r_m)/\sigma$ with $\Delta\rho$ the difference of fluid densities, r_m the distance from the middle of the sample to the centrifuge axis, σ the interfacial tension.
Limitations of this method have been studied and are well defined. The first assumption, the capillary end effect is negligible, leads to the choice of a minimum rotational speed to overcome this effect. This may be characterised by the capillary-gravity number $N_{cg} = P_c^*/(\Delta\rho\omega^2 r_m L)$, with P_c^* being a characteristic capillary value and L the sample length [10]. Saeedi and Pooladi-Darvish [10] suggest a N_{cg} upper bound of 10^{-2}. Below this value, i.e. a critical rotational speed, the Hagoort calculation will underestimate the displaced fluid relative permeability and overestimate the final saturation (S_{wi} in a case of a gas-water drainage) [11].
In order to illustrate these observations, we performed the Hagoort calculation on several numerical experiments with different rotational speeds from 750 to 10 000 rpm and for several viscosity ratio $M = \mu_{disp}/\mu_{in}$ 0.1, 1, 10 and 100. The subscript *disp* stands for displaced fluid and *in* for invading fluid. Typically water-gas system would be around M=50. Figure 1 shows the capillary pressure used. Figure 2 compares the interpreted K_r with the K_r used for the simulation (bold line). It confirms that Hagoort calculation underestimates the relative permeability and overestimates the Swi. Table 1 resumes the gravity number, the Bond number and the error between Hagoort calculation K_{rH} and the initial K_r. The error calculated over *n* points is defined as: $Err = \frac{\Sigma|K_r - K_{r_H}|/n}{\max(K_{r_H}) - \min(K_{r_H})}$.

The Bond number is well below the Hagoort limit, and this seems to confirm the Saeedi N_{cg} upper bound of 10^{-2} with error under about 20%.

Multi-speed experiment, the Forbes P_c calculation [5, 6]
Forced drainage or imbibition are performed by rotating a core at various rotational speed. Fluid production is then measured at equilibrium for every rotation speed. The average saturation $\bar{S}(P_c)$, derived from the effluent production volume, is linked to the capillary pressure, P_c, at equilibrium as follow:

$$\bar{S}(P_c) = \frac{1}{L\pi R^2} \int S(P_c)dv \qquad (4)$$

with L being the core length, R its radius, dv the elementary volume and $S(P_c)$ the local capillary curve. The difficulty is to inverse equation (4), i.e. to derive $S(P_c)$ from $\bar{S}(P_c)$ since there is no exact solution. A large amount of experimental and theoretical work has been devoted to this problem, see references in the Forbes' SCA survey [6]. The three main methods are:

- The Hassler and Brunner method [12] based on an assumption of uniform centrifuge forces, leading to an analytical calculation of the local P_c curve. This solution is not accurate but has a historic interest.
- The Forbes' method [5], more exactly the discrete solution of the second method equations 18 and 21 in reference [5]. We will come back below on the accuracy of this method.
- The splines method [13], the purpose is to describe the P_c curve with splines or B-splines and then to optimize the splines parameters to fit the experimental data.

Multi-speed experiment, K_r calculation
Relative permeability can be determined from the transient of production using numerical history matching [7, 8, 9].

SAMPLE AND EXPERIMENTAL SET-UP

Sample
The sample used in this study has been plugged in a saline aquifer of the Triassic Stuttgart formation located close to Berlin. The sandstones of this formation are of fluvial origin. They consist of varying amounts of quartz, feldspar, and rock fragments, classifying them as graywacke. They are fine-grained to medium-grained, well-sorted and locally highly cemented by clay and silicates [14]. The geometrical and petrophysical properties of the sample are given in Table 2.

Experimental set-up
Saturation measurements while spinning are usually performed using optical devices. For this study, we used a specific automatic in-house built centrifuge. The principles of this centrifuge are described in details in Fleury et al. [15]. The system records continuously the amount of water expelled from the sample and rotational speed as a function of time. The originality of the device remains on the detection system that uses capacitance measurements. Figure 3 is a scheme of the core holders in the centrifuge. The rotating contact, which has been developed by IFPEN allows the signals from the level detectors

to be transmitted to the level analyser outside the centrifuge. Figure 4 is a scheme of the core holder. On this scheme are reported the position of the plug in drainage and in imbibition experiments. The position of the level sensor is also indicated. The sensor is a capacitance made of a metallic rod with a thin isolating ceramic coating. This detector is sensitive to the height of the conductive fluid (brine) in which the sensor is immersed. The accuracy is about 0.05 cc, which is better than 1% of the pore volume in the specific case of this study (Figure 7).

Experiments
Two water-air drainages were performed: a single speed at about 2000 rpm, and a 9 step multi-speed experiment with rotational speeds between 500 and 2000 rpm. A mercury injection was also performed in order to test the improvement in K_r calculation using an approximate P_c curve. The drainage P_c curve is derived using the J Leverett function. The S_{wi} is the mercury saturation at a P_c value corresponding to our mono-speed experiment, i.e. around 2 bar.

RESULTS AND DISCUSSION
The interpretation of the multi-step experiment is done in two steps: first the determination of the local P_c curve, then the K_r optimization by history matching. This method works very well with synthetic data where the P_c curve is known but we had difficulties with real experiments. We discovered that the standard Forbes method was not accurate enough to catch the real level of the stabilized production.
We will now illustrate the limitation of the method presented by Forbes and present how to improve it.

Improvement of Forbes method
We call it the "discrete" Forbes method since the calculation is based on the differences between data points (see equations 18 and 21 ref. [5]). The limited number of points introduces an error, like any finite difference method compared to analytical calculation. Forbes gave a limit of about 5 points [5]. When we use this discrete method, we are confident since the calculation of the average $P_c(\bar{S})$ points gives back the experimental ones. But this is misleading since the backward calculation of the discrete differencing scheme will always give back the experimental points.
To improve the method, we need to fit the experimental points and then apply on it the continuous form of the Forbes method (equations 15 and 20 ref. [5]) performing numerical integrations and differentiations. The type of smoothing curve depends on the number of experimental points. With a large number of points, a spline smoothing catches the details of the curve, but a hyperbolic fit or Hermite interpolation is better for 5 points or less.
To illustrate the difference between discrete and continuous methods, we use an analytical case presented by Chen and Ruth [16] where both local and average P_c are known analytically, P_c in psi:

$$S(P_c) = \begin{cases} \dfrac{1.5}{P_c} + 0.25 & \text{if } P_c \geq 2 \\ 1 & \text{if } P_c \leq 2 \end{cases} \qquad (5)$$

Figure 5 shows the local P_c and average $P_c(\bar{S})$ curves obtain using both methods and the theoretical curves. The continuous approach implemented in the software CYDAR, gives good results when the discrete solution gives a local P_c slightly shifted. The error with the discrete solution does not seems significant but if we look at the production curve done with the three local P_c curves (Figure 6) it appears that the discrete method is far from the exact solution.

Multi-speed experiment
Figure 7 shows the experimental data and the simulation. The local P_c derived using the Forbes continuous method is used as 1st guess. The relative permeabilities are then optimized. The K_r used here are Hermite interpolations between 5 knots. The P_c curve is finally slightly optimized for the best fit.

Mono-speed experiment
Figure 8 shows the experimental data with three K_r determinations by history matching, S_{wi} being optimized as well, using the recorded speed and different P_c curves: the mercury capillary pressure, the multi-steps P_c and no capillary pressure. These optimized K_r curves are displayed on Figure 9 together with the K_r determined from the multi-step experiment, and the standard analytical Hagoort method.

Discussion
From Figure 9, it is clear that the result of the analytical Hagoort calculation differs from the K_r obtained by numerical history matching. There are two reasons:

1. Capillary effects: The numerical simulation with $P_c=0$ shows the same overestimation of S_{wi} than the Hagoort curve. This error is related to the capillary end effect and could be improved only with higher rotation speed.
2. Initial speed ramp: The centrifuge always takes a few minutes to reach the selected speed (ramp around 650 rpm/min). During this startup regime, the production is less than expected in the analytical model that assumes instantaneous constant speed. Consequently the interpreted K_r is less than the true value. This effect on the Hagoort calculation has already been reported [17] and explains the lower value at high liquid saturation. In order to verify this assumption, we have simulated a displacement with the K_r and P_c of the mercury case, with a perfectly constant speed. When interpreted with Hagoort, the K_r value is close to the other determinations at high saturation (curve noted K_r Hagoort no ramp on the graph).

The Hagoort calculation has the advantage that it does not need any simulator, but may lead to significant error on K_{max} and S_{wi} in normal centrifuge use as in our example (M=50, ω=2000 rpm).
However, the results shown in Figure 9 demonstrate that mono-speed experiment can be improved using numerical history matching taking into account:

1. The real speed of the centrifuge, to improve the K_r at high saturation value. Most of centrifuges with production monitoring record the speed. If not, it is always easy to add an optical tachymeter to record the speed.
2. The capillary pressure which has obviously a strong effect [18, 19]. Here an approximate drainage P_c curve derived from mercury measurement on a companion sample improves the results.

The multi-steps experiment takes more time but allows the estimation of both capillary pressure and relative permeabilities. Reducing the number of steps may reduce the duration of the experiment. We have studied the optimum number of steps. Increasing the number of steps gives better accuracy on P_c but less on K_r, since the production is closer to equilibrium. In the limit of a very slow experiment, with infinite number of steps, it would not be possible to derive the K_r. Figure 10 shows water relative permeability and capillary pressure curve calculated from three synthetic multi-steps experiments at 4, 6 and 8 steps. The K_r figure indicates that 6 steps experiment gives the best results. So the duration of the experiment can be reduced from 90 hours to 30 hours for 6 steps. For less permeable samples, numerical simulations show that the gas/liquid centrifuge does not exceed a few days for 6 steps.

Another way to reduce experimental time is to reduce steps duration and not wait till stabilization, the end step saturations being estimated using a bi-exponential function on each step [20].

CONCLUSION

The conclusions of this study for gas/liquid mono and multi-speed centrifuge experiments are the following:

1. The standard Forbes method used in most of laboratories to derive the local P_c curve is not accurate for a limited number of points and the Forbes calculation of the average P_c used as control is wrong and misleading. The method is improved by fitting the experimental data and using a large number of points of the fitted curve for the Forbes calculation. As a quality control, it is recommended to always display the recalculated average saturation, not using Forbes formula, but using a standard numerical integration.
2. Hagoort analytical calculation from a mono-speed experiment underestimates the relative permeability maximum due to the time needed by the centrifuge to reach the selected speed.
3. Hagoort overestimates the final liquid saturation (Swi) since capillary end effects are not taken into account.
4. Interpretation of mono-speed experiments is improved by using history matching with a numerical simulator that accounts for the real speed of the centrifuge and takes into account the capillary pressure using for instance a P_c curve derived from mercury injection.
5. For gas drainage, multi-step experiments take more time than a mono-speed experiment but never exceed a few days. They can be considered as the best compromise between cost and quality of data, since they provide both K_r and P_c.

REFERENCES

1. van den Berg, E. H. , Perfect, E., Tu, C., Knappe, P. S. K., Leao, T. P., Donat, R. W., "Unsaturated Hydraulic Conductivity Measurements with Centrifuges: A Review", *Vadose Zone J.*, Vol. 8, No. 3, 531-547, 2009.
2. Ruth, D., "The Constantly-Accelerating Centrifuge Revisited", SCA-9812, 1998.
3. Ruth, D., "A Proposal For A Constant Flow Rate Centrifuge Technique To Measure Relative Permeability And Capillary Pressure", SCA-0606, 2006.
4. Hagoort, J., "Oil Recovery by Gravity Drainage", *SPEJ*, 139-149, June 1980.
5. Forbes, P., "Simple And Accurate Methods For Converting Centrifuge Data Into Drainage And Imbibition Capillary Pressure Curves", SCA-9107, 1991.
6. Forbes, P., "Centrifuge Data Analysis Techniques: A Sca Survey On The Calculation Of Drainage Capillary Pressure Curves From Centrifuge Measurements", SCA-9714, 1997.
7. O'Meara, D.J. Jr. and Crump, J.G., "Measuring Capillary Pressure and Relative Permeability in a Single Centrifuge Experiment", SPE 14419 presented at the *SPE Annual Technical Conference and Exhibition*, Las Vegas, Nevada, 22-25 September 1985.
8. King, M. J., Narayanan, K.R., Falzone, A.J., "Advances in Centrifuge Methodology for Core Analysis", SCA paper 9011, 1990.
9. Nordtvedt, J.E., Watson, A.T., Mejia, G., Yang, P., "Estimation of Capillary Pressure and Relative Permeability Functions From Centrifuge Experiments", *SPERE*, 292-298, November 1993.
10. Saeedi, M., Pooladi-Darvish, M., "Revisiting the Drainage Relative Permeability Measurement by Centrifuge Method Using a Forward–backward Modeling Scheme", *Transp Porous Med*, Vol. 86, 49–71, 2011.
11. Singh, M., Mani, V., Honarpour, M.M., Mohanty, K.K., "Comparison of viscous and gravity dominated gas–oil relative permeabilities", *J. Pet. Sci. Eng.* Vol. 30, 67-81, 2001.
12. Hassler, G.L., Brunner E., "Measurement of capillary pressures in small core samples", *Trans. Am. Inst. Min. Metall. Eng.* Vol. 160, 114-123, 1945.
13. Nordtvedt, J. E., Kolitvelt, K., "Capillary pressure curves from centrifuge data by use of spline functions", *SPERE*, 497-501, November 1991
14. Förster, A., Norden, B., Zinck-Jørgensen, K., Frykman, P., Kulenkampff, J., Spangenberg, E., Erzinger, J., Zimmer, M., Kopp, J., Borm, G., Juhlin, C., Cosma, C., Hurter, S., "Baseline characterization of the CO2SINK geological storage site at Ketzin, Germany", *Environ. Geosci.*, Vol. 13, No. 3, 145-161, September 2006.
15. Fleury M., P. Poulain and G. Ringot, "A capacitance technique for measuring production while centrifuging", SCA-9833, 1998
16. Chen Z. A., Ruth D. W., "Centrifuge Capillary Pressure Data Reduction with a Modified Forbes Method", *J. Pet. Sci. Eng.* Vol. 9, 303-312, 1993.

17. Hirasaki, G. J., Rohan, J. A., Dudley, J. W., "Interpretation of Oil-Water Relative Permeabilities from Centrifuge Experiments", *SPE Adv. and Tech.*, Vol.3, No. 1, 66-75, 1995.
18. Skauge, A., Haskjold, G., Thorsen, T., Aarra, M., "Accuracy Of Gas-Oil Relative Permeability From Two-Phase Flow Experiments", SCA-9707, 1997.
19. Skauge, A., Poulsen, S., "Rate Effects on Centrifuge Drainage Relative Permeability", SPE 63145 presented at the *SPE Annual Technical Conference and Exhibition,* Dallas, Texas, 1-4 October 2000
20. Fleury, M., Egermann, P., Goglin, E., "A model of capillary equilibrium for the centrifuge technique", SCA-2031, 2000.

Table 1. capillary-gravity number, bond number, Hagoort relative permeability error versus viscosity ratio and rotational speed.

M		0.1			1		
ω	P_c (bar)	N_{cg}	N_b	Err ()	N_{cg}	N_b	Err ()
750	0.3	$2.7\ 10^{-1}$	$2.2\ 10^{-6}$	107.4	$2.7\ 10^{-1}$	$2.2\ 10^{-6}$	56.6
1500	1.2	$6.6\ 10^{-2}$	$8.8\ 10^{-6}$	40.5	$6.6\ 10^{-2}$	$8.8\ 10^{-6}$	20.5
3000	4.7	$1.7\ 10^{-2}$	$3.5\ 10^{-5}$	31.2	$1.7\ 10^{-2}$	$3.5\ 10^{-5}$	14.2
4500	10.6	$7.4\ 10^{-3}$	$7.9\ 10^{-5}$	37.1	$7.4\ 10^{-3}$	$7.9\ 10^{-5}$	12.9
10000	52.3	$1.5\ 10^{-3}$	$3.9\ 10^{-4}$	63.3	$1.5\ 10^{-3}$	$3.9\ 10^{-4}$	12.0
M		10			100		
750	0.3	$2.7\ 10^{-1}$	$2.2\ 10^{-6}$	41.5	$2.7\ 10^{-1}$	$2.2\ 10^{-6}$	37.8
1500	1.2	$6.6\ 10^{-2}$	$8.8\ 10^{-6}$	10.3	$6.6\ 10^{-2}$	$8.8\ 10^{-6}$	5.7
3000	4.7	$1.7\ 10^{-2}$	$3.5\ 10^{-5}$	3.2	$1.7\ 10^{-2}$	$3.5\ 10^{-5}$	1.6
4500	10.6	$7.4\ 10^{-3}$	$7.9\ 10^{-5}$	2.7	$7.4\ 10^{-3}$	$7.9\ 10^{-5}$	0.8
10000	52.3	$1.5\ 10^{-3}$	$3.9\ 10^{-4}$	2.5	$1.5\ 10^{-3}$	$3.9\ 10^{-4}$	0.8

Table 2. sample properties

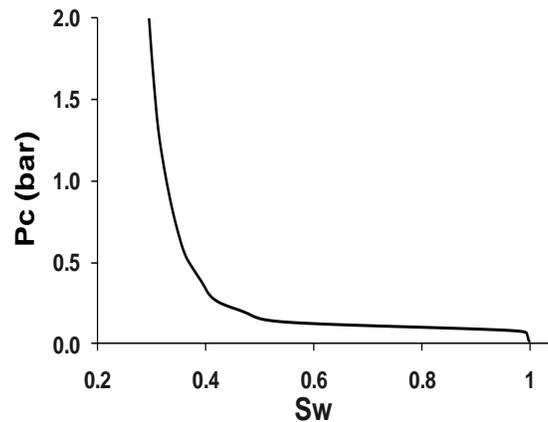| Length (mm)	Diameter (mm)	Porosity (%)	Pore volume (cc)	Permeability (mD)
24.2	39.7	28.1	8.4	230

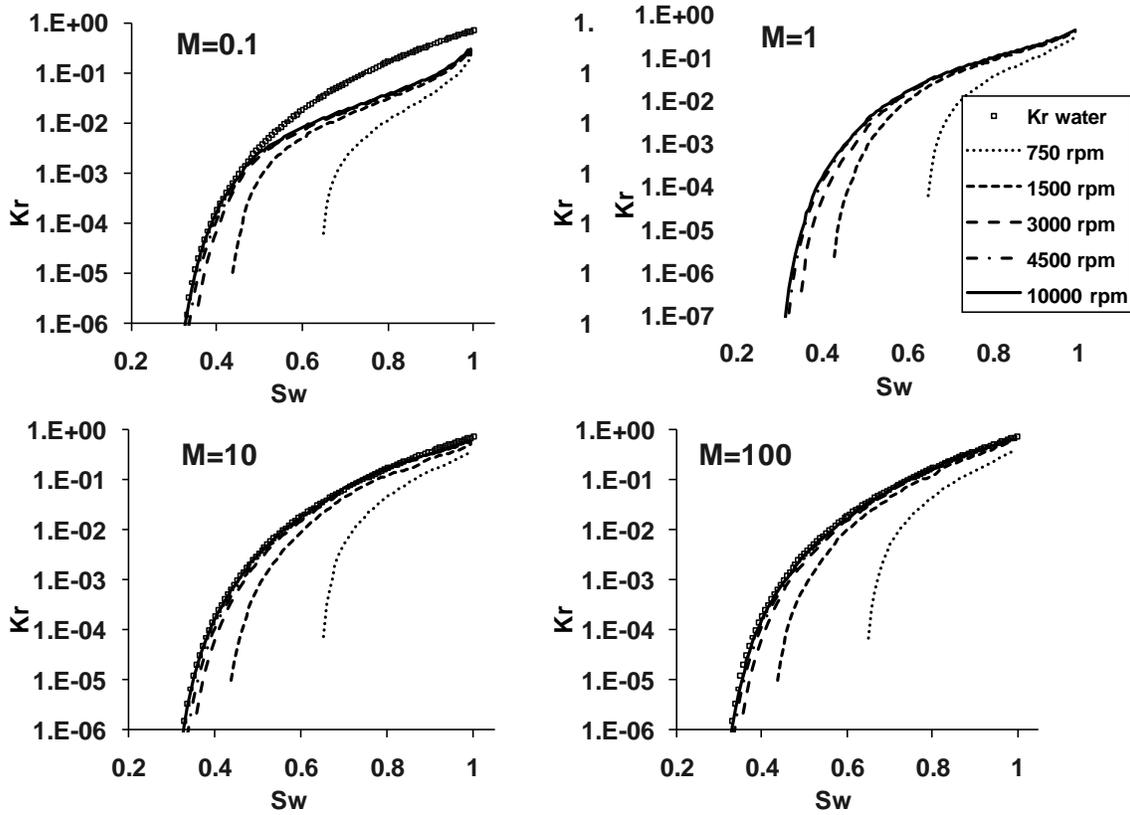Figure 1: Capillary pressure used to create numerical experiments

Figure 2. Viscosity ratio and rotational speed effects on Hagoort calculation.
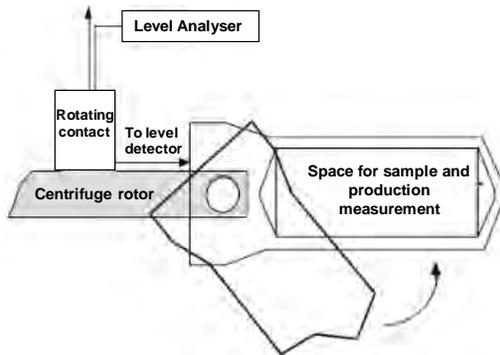

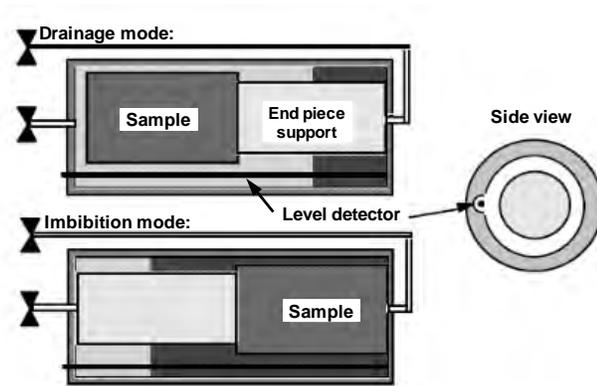Figure 3. Schematic of the core holders in the centrifuge.

Figure 4. Centrifuge core holders in drainage and forced imbibition mode. The level detector located on the side (top view) is connected to the level analyzer through a rotating contact (slip ring assembly).
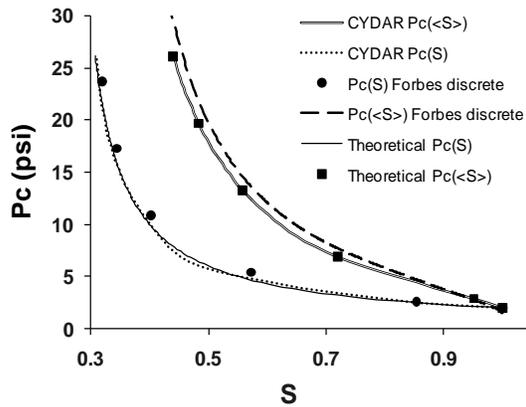
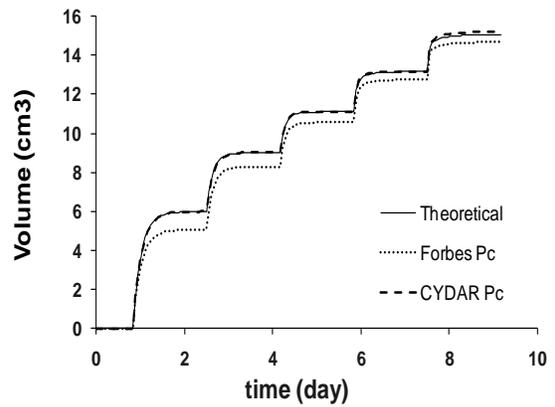Figure 5: Analytical case with 6 points, comparison with Forbes SCA 1991 and CYDAR optimization tool.

Figure 6: Production simulation using a theoretical local P_c, the Forbes' discrete solution and the continuous approach.
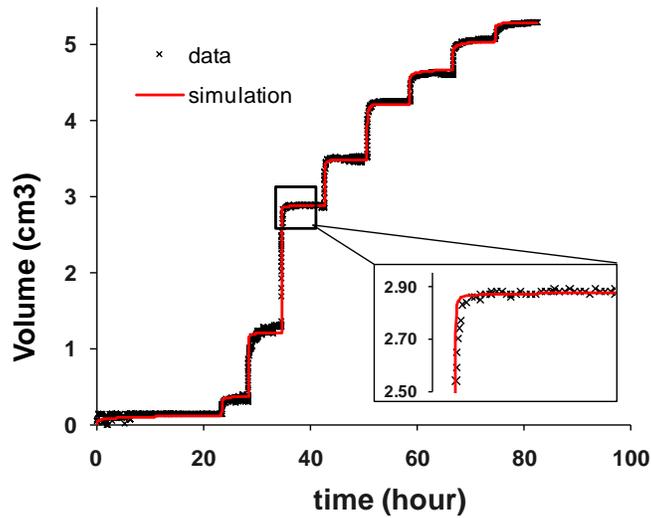
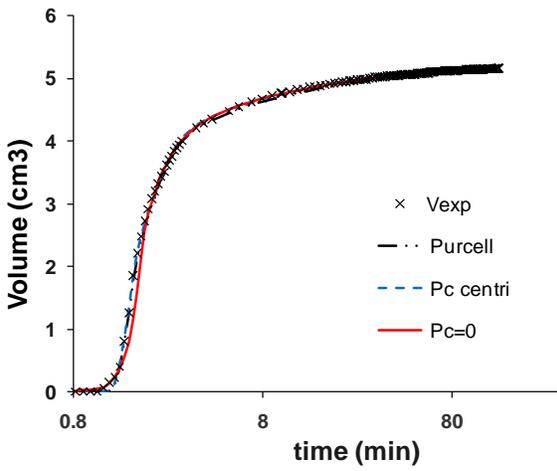Figure 7: K_r and P_c optimization, experimental data simulation

Figure 8: mono-speed experiment, K_r optimized with mercury P_c, multi-steps P_c and P_c =0.
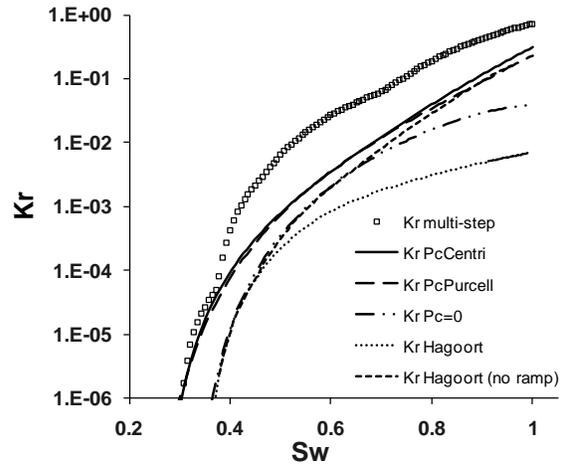

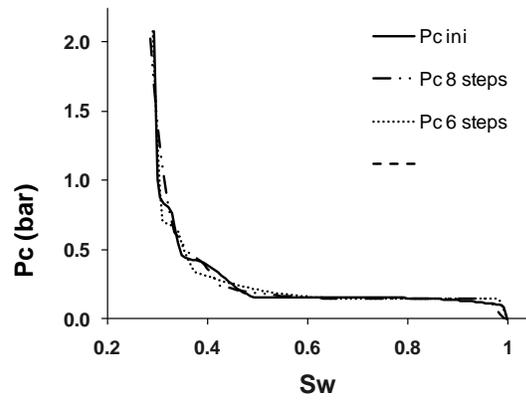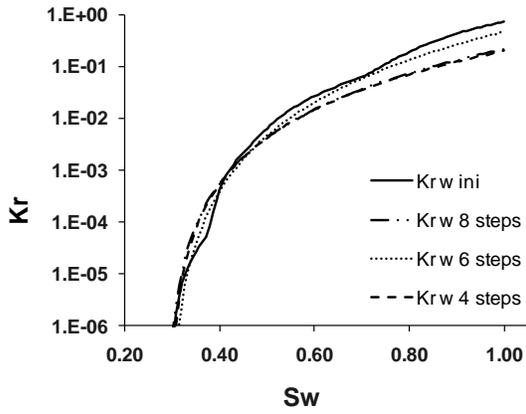Figure 9: comparison of water relative permeabilities mono-speed experiment

Figure 10. multi-speed experiment: effect of the number of steps on water K_r estimation and on P_c.