WATER OIL RELATIVE PERMEABILITY COMPARATIVE STUDY: STEADY VERSUS UNSTEADY STATE

[1]Marcelo M. Kikuchi, [1]Celso C.M. Branco, [2]Euclides J. Bonet, [2]Rosângela M.Zanoni, [1]Carlos M. Paiva
[1]Petrobras Research Center, [2]State University of Campinas (Unicamp)

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Toronto, Canada, 21-25 August 2005

ABSTRACT

The main objective of this paper is to discuss the methodology and results of a comprehensive study aiming the comparison of water/oil relative permeability curves measured by unsteady-state (USS) and steady state (SS) methods in outcrop rock samples with refined mineral oils. The US and SS comparison work was preceded by a repeatability study followed by a sensitivity study. The sensitivity study evaluated parameters such as oil viscosity, rock permeability and the flow regime (SS or USS) which were combined based on an experimental design.

More than 20 tests were performed and analyzed using response surface methodology. The absolute permeability of the rock has been shown to be the most important parameter affecting oil recovery factor and end point permeabilities. As expected, oil viscosity did not present any significant effects up to 100 cp.

One important feature of the steady state process is its ability to provide relative permeability information for water saturations below unsteady state water breakthrough. These data may be useful for light oil reservoirs where piston-like displacements often occur. It may also be useful for viscous oil reservoirs since it can provide a more detailed characterization of the displacement in a situation where a water shock front does not develop. Some reservoir simulations were performed in order to evaluate the impact of different processes of relative permeability determination focusing on the pre-breakthrough saturation range.

INTRODUCTION

Although relative permeability has been widely studied for years, a lot of doubts still remain concerning which parameters affect it most and how accurately they must be determined in the laboratory. For instance, although unstabilized displacements do not respect the assumptions of Buckley Leverett's [1] displacement theory, the JBN [2] method is usually used for relative permeability calculations. The same unstable flow problem occurs in other situations as when heterogeneous samples are tested or when capillary end effects are present [4]. History matching determination procedure may be useful in this situation but its does not assure the uniqueness of the solution. In addition, the JBN method is able to provide relative permeability only for saturations higher than water breakthrough saturation (Swbt). However, for light oils the breakthrough happens when oil saturation is near to residual value. Therefore, unsteady state experiment does not provide data between initial water (Swi) and Swbt.

As an advantage, unsteady-state takes few hours to conclude the displacement instead of weeks (several days) for steady-state testing. On the other hand, the SS is able to provide relative permeability information in a larger saturation range. The SS relative permeability calculation procedure is straightforward and very simple by applying Darcy's law.

PROCEDURES

The relative permeability tests were performed under unsteady-state and steady-state flow regime in outcrop rock samples using refined mineral oils at ambient temperature. The flow rate used was 2 cm^3/minute. The absolute permeability and oil viscosity were separated into two different groups (levels) as shown in Table 1. The scattering in absolute permeability values within each of the two core groups used in the study was not considered important in the analysis and conclusions since the permeability magnitude of the two groups is much different. The scaling coefficient for those experiments (length * viscosity * velocity) were kept to3.2 up to 4.8 cm^2.cP/minute to provide a stabilized flooding as suggested by Rapoport and Leas [5]. Under stabilized conditions, the linear waterfloods are supposed to be independent of rate, length and viscosity. The comparisons made on this study considered only the end points of relative permeability curves to allow their treatment by statistical analysis.

The simulation study was performed in a real reservoir model using several USS curves and comparing their results with SS curve. The USS curves were obtained by fitting different Corey models in the selected USS curve previously determined by JBN method, whose coefficients are presented in the Table 3. Since the oil viscosity in the USS and SS test was low, a typical piston like displacement had been obtained in USS test. In this situation, the simulation is usually performed admitting a linear interpolated data for saturation before breakthrough. Different Corey model fittings were done in order to get different interpolation in the USS curve and compare their simulation results with the SS one. Both USS and SS curve were obtained from the same rock sample and oil. SS end points curve were adjust to match to USS one.

RESULTS

An example of repeatability obtained is presented in Figure 1. The curves were measured by unsteady-state method in two different situations using JBN method. The curves 1 and 2 were obtained for a high permeability rock (4 Darcy) using a 1.2 cP viscosity oil. Curves 3 and 4 were obtained for a low permeability rock (0.2 Darcy) using a 130 cP viscosity oil. For both situations, considering the small dispersion of results, the repeatability obtained was considered adequate.

The analysis of variance (ANOVA) for oil viscosity, permeability and flow regime effects on recovery factor was evaluated. Recovery factor is defined as the ratio between cumulative oil produced in an experiment and the original oil in place. As shown in Table 2, the absolute permeability was the most important parameter according to the “p” value which represents the level of significance or probability. This can also be observed in the fitted surface response shown in Figure 3 and Figure 4. A graphic display of the quality of fitting is shown in Figure 2. In the Figure 3 the recovery factor is presented as function of absolute permeability and oil viscosity, while in Figure 4 the recovery factor is presented as a function of absolute permeability and flow regime. Flow regime and viscosity do not have significant effect. Likewise the combined effects among absolute permeability and oil viscosity (denoted by 1 by 2 in Table 2), permeability and flow regime (denoted by 1 by 3 in Table 2) and viscosity and flow regime (denoted by 2 by 3 in Table 2).

The effects of those parameters on residual oil saturation (Sor) and water relative permeability (krw) at residual oil saturation are presented in Figure 5 and 6. The absolute permeability is shown to be the most important effect.

As commented before, the USS method does not provide relative permeability information for saturation values between Swi and Swbt. In the lack of this information, simulations are usually performed with interpolated data for this range. This interpolated curve may differ from the steady-state curve even when the end points are adjusted to be the same, as was done in this study. For instance, in the Figure 7 are shown the USS and SS curves obtained in the same rock sample and light oil. The USS curve was obtained by JBN (curve 5) and is also approximately represented by a Corey interpolation with nw=1.2 (curve 6). The same figure also depicts the steady-state curve (curve 9) which was considered as the correct one (its end points had been adjusted to be the same of USS). More two sets of curves were obtained using different Corey exponent (curves 7 and 8) only to show the impact of choosing different fitting.

A reservoir simulation was performed using all the different sets of curves from Figure 7 on a real offshore 17 API oil sandstone reservoir. The results are presented in Figure 8. It can be easily shown the impact that different interpolation processes had on the recovery factor. In this particular reservoir the Corey curve calculated with nw=5 provided the response closest to the SS one. Nevertheless this cannot be adopted as a rule; so it is always advisable to have a good description of the pre breakthrough water relative permeability curve.

CONCLUSIONS

A comparison between relative permeability curves obtained through tests unsteady-state and steady state flow regimes was performed on water wet rock samples using refined mineral oils.

Based solely on the analysis of variance (ANOVA) of end points the following three conclusions can be drawn.

1) The absolute permeability had the most important effect on recovery factor.

2) Absolute permeability was also the most important variable on the residual oil saturation and water relative permeability end points.

3) The flow regime and oil viscosity do not provide a significant effect on recovery factor.

The shape of water relative permeability curves obtained by steady-state showed some differences to the unsteady-state curve, which was obtained with the same sample and using the same fluids system, even when end points obtained were similar, as shown in Figure 7.

The simulation of a real reservoir using different unsteady-state curves with interpolated data for the saturation region before water breakthrough may yield different oil recoveries when compared to a steady-state curve.

ACKNOWLEDGMENTS

The author is very thankful to Petrobras for the opportunity to develop this study.

REFERENCES

1 Buckley, S.E. and Leverett, M.C. “Mechanism of Fluid Displacement in Sands” PetroleumTransaction, AIME, (1942) p.107-116
2 Johnson, E.F., Bossler, D.P, Naumann, V.O. “Calculation of Relative Permeability from Displacement Experiments” PetroleumTransaction, AIME, (1959).
3 Jones, S.C., Roszelle, W.O. “Graphical Techniques for Determining Relative Permeability From Displacement Experiments”. Journal of Petroleum Technology (May 1978), p.807-817.
4 Murali, R. “Evaluation of Effect of Capillary Forces on Measurements in Linear Waterfloods by Simulation”, presented at the International Symposium of Society of Core Analysts at Pau France. September 2003.
5 Rapoport, L.A. e Leas, W.J.: “Properties of Linear Waterfloods” Trans. AIME (1953) Vol 198 – Pp 139-148.
6 Welge, Henry J. “A Simplified Method for Computing Oil Recovery By Gas or Water Drive” Trans. AIME, (1952). Vol. 152, p.91-98.).

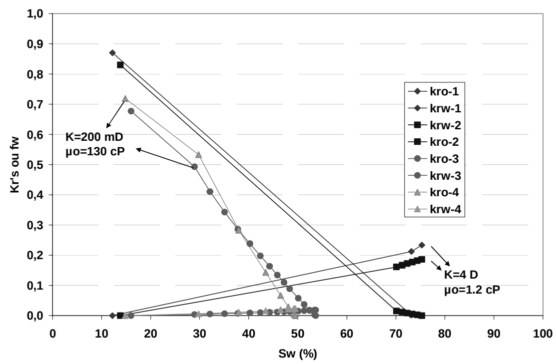

Figure 1 – Example of repeatability obtained.

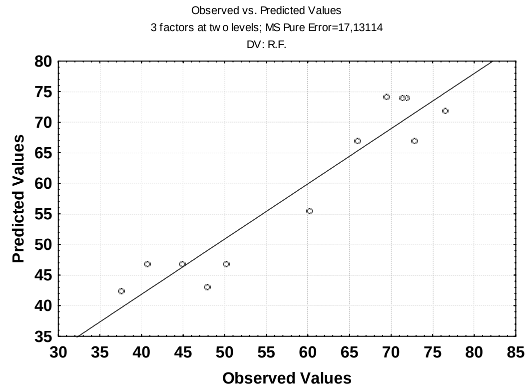

Figure 2 – Fitted function on experimental data of recovery factor.

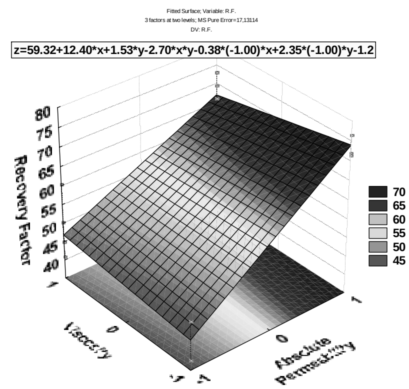

Figure 3 – Recovery Factor

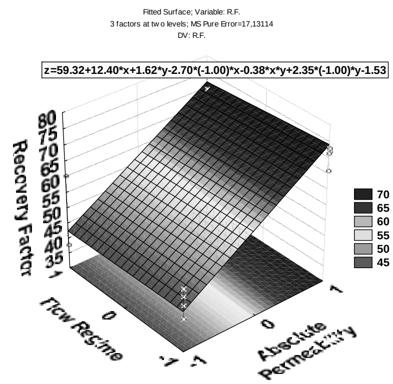

Figure 4 – Recovery Factor

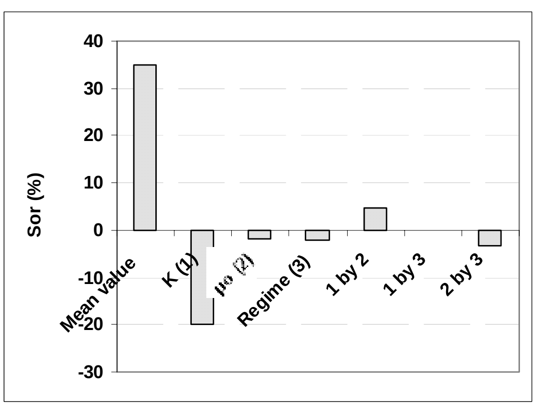

Figure 5 – Variability effects on residual oil saturation

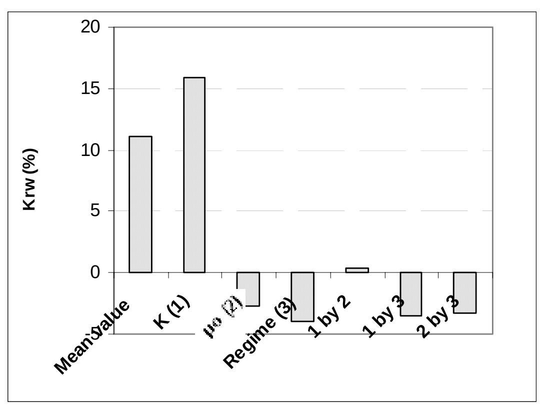

Figure 6 – Variability effects on water relative permeability end point

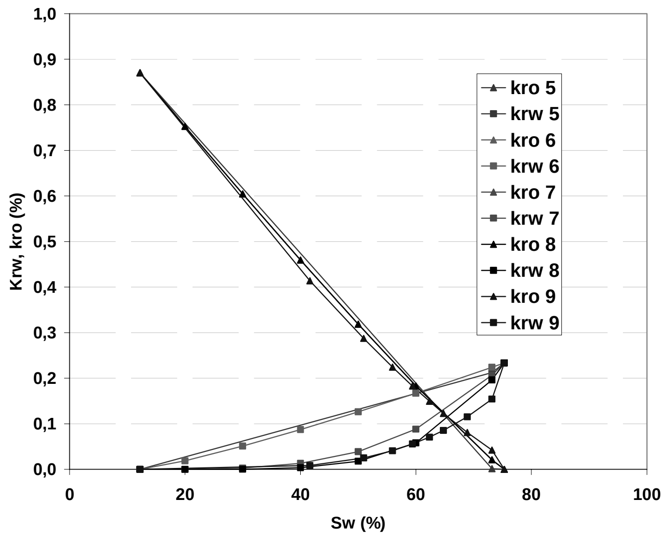

Figure 7 – Corey model fitted curves used in simulation.

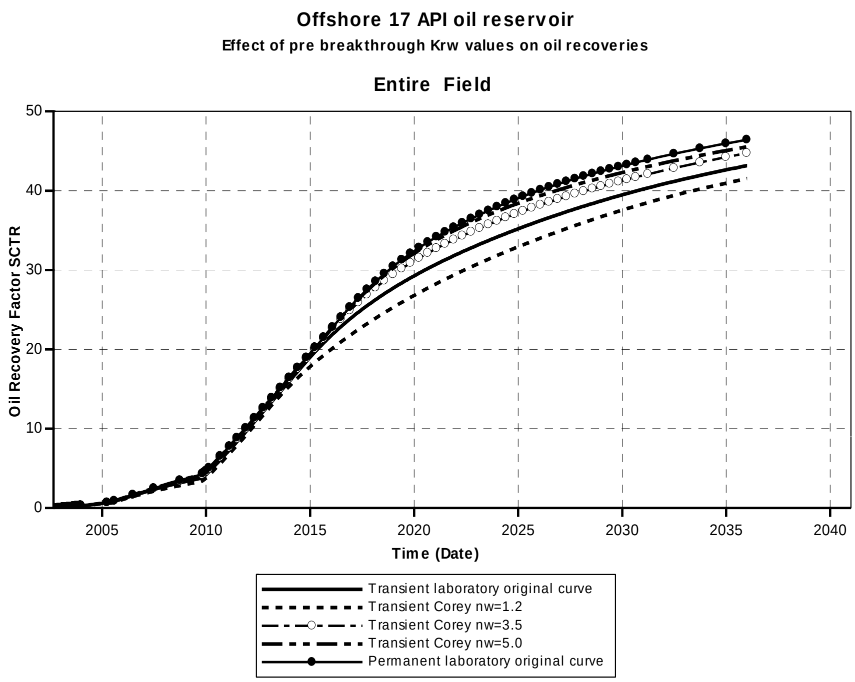

Figure 8 – Recovery factor for 17API oil, real sandstone offshore reservoir developed through horizontal production and injection wells.

Table 1 – Classification of parameters

	High level (+1)	Low level (-1)
Absolute permeability (D)	> 4	< 0.5
Oil viscosity (cP)	130	1.2
Flow regime	Steady-State	Unsteady-State

Table 2 – Analyses of variance for 3 factors at 2 levels

	SS	df	MS	F	p		
(1) K	1570,801	1	1570,801	91,69273	0,000665		SS - Sum of Squares
(2) Visco	23,800	1	23,800	1,38931	0,303849		df - degrees of freedom
(3) Wet	26,753	1	26,753	1,56166	0,279550		MS - Mean Square
(1) por (2)	78,760	1	78,760	4,59746	0,098625		F - F distribuition
(1) por (3)	1,458	1	1,458	0,08512	0,784983		p - p values
(2) por (3)	55,788	1	55,788	3,25650	0,145462		
Lack of Fit	143,134	1	143,134	8,35520	0,044539		
Pure Error	68,525	4	17,131				
SQ Total	2170,614	11					

Table 3 – Curves used in simulation study

nw	no	Curve	Observation
-	-	5	Original USS
1,2	1,1	6	Fitted Corey in Curve 5
3,5	1,1	7	Fitted Corey in Curve 5
5	1,1	8	Fitted Corey in Curve 5
-	-	9	End points adjusted SS