A NEW ALGORITHM FOR ESTIMATING THREE-PHASE RELATIVE PERMEABILITY FROM UNSTEADY-STATE CORE EXPERIMENTS

Hamidreza Shahverdi, Mehran Sohrabi and Mahmoud Jamiolahmady
Institute of Petroleum engineering, Heriot-Watt University, Edinburgh, UK

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Halifax, Nova Scotia, Canada, 4-7 October, 2010

ABSTRACT

Relative permeability (kr) values are usually measured in core laboratories using steady-state or unsteady-state coreflood experiments. In this paper we present a new history matching method based on Genetic Algorithm (GA) to estimate three-phase kr from unsteady state coreflood experiments. In this method, relative permeabilities are represented by quadratic B-Spline functions. Adjustable coefficients in kr functions are changed in an iterative process to minimize an objective function. The objective function is defined as the difference between the measured and simulated values of the pressure drop across the core and fluid recovery during the experiment. One of the main feature of the new algorithm is that water and gas relative permeabilities (krw and krg) are assumed to be functions of two independent saturations as opposed to most of the existing empirical kr models in which krw and krg are assumed to be only dependant on their own saturation. Another important aspect of the new algorithm is that it considers inequality constraints to ensure that physically acceptable kr curves are maintained throughout the iterative optimization process. Capillary forces in fluid flow simulation have also been incorporated in this algorithm.

Based on the new algorithm, a computer program has been developed that produces kr values by matching experimental data through minimising the objective function. The results of some three-phase coreflood experiments that we have performed in our laboratory have been used to obtain three-phase kr curves by this approach. The integrity of the method and the accuracy of the results have been verified by Eclipse 100.

INTRODUCTION

In the unsteady state method, relative permeability can be obtained either by explicit or implicit methods. The Johnson-Bossler-Naumann (JBN) (Johnson et al, 1958) which is the most commonly used explicit method is based on Buckley- Leverett displacement theory. In this method the relative permeability of each phase is calculated by utilizing the derivative of the pressure drop across the core and the fluid production curves after the breakthrough of the displacing phase. JBN method is usually tedious and can result in significant errors in estimating kr values. Moreover, in many unsteady state coreflood experiments, the production of the displaced phase usually stops a short time after the breakthrough of the displacing phase, thus kr values can only be obtained for a very limited range of fluids saturations. Also, capillary pressure can not be readily incorporated in this approach.

In implicit (or parameter estimation) methods, relative permeability are selected so that the misfit value between the observed and simulated values of fluid production, pressure and saturation is minimized (Kerig et al, 1986, Mejia, 1996, Richmond,1988). To use this approach, a functional form containing tuning parameters is selected to represent each phase's kr. Then matching the experimental data is repeatedly attempted by changing these coefficients until the closest match is obtained.

In this paper we present a new algorithm for obtaining kr values from unsteady-state experiments. In our approach, three-phase kr curves are determined by matching the fluid recoveries and differential pressure data obtained from three-phase displacement core tests. We have developed a computer program for this task based on a genetic algorithm. The program is designed to generate best estimates of three-phase relative permeability based on suitable mathematical functions defined to describe their dependency to phase saturations. In our approach no presumption is made regarding the dependency of the multiphase flow functions to a specific saturation.

THEORY

The methodology consists of three principle components. First, a mathematical model is chosen to represent the fluid flow through porous media. The model should be adequately comprehensive such that all important physical effects within the displacement experiment are represented. The second element of implementing this approach is a functional representation for relative permeability curves that need to be estimated and the third element is an optimization tool which is utilized to minimize the objective function (Bard, 1974).

Mathematical model

Using continuity equation for immiscible flow of each phase through porous media including Darcy equation as momentum term results in the following equation:

$$\nabla.\left[\frac{kk_{ri}}{\mu_i}\left(\nabla P_i - \rho_i \frac{g}{g_i}\nabla z\right)\right] = \frac{\partial(\phi S_i)}{\partial t} + q_i \qquad i= oil, gas, water \qquad (1)$$

In this study the fluids and rock compressibility are neglected due to the typical high pressure at which the displacements occur.

Relative permeability function

The unknown functions to be estimated must be represented with a finite number of parameters. This is accomplished through the selection of functional representations for the parameters to be estimated. This is achieved very well for the two-phase case through the use of B-splines functions. This approach has been extended to the three-phase case representing the flow functions using B-spline which is given by:

$$k_{ri}(S_I, S_{II}) = \sum_{k=1}^{m+n}\sum_{l=1}^{m+n} a_{k.l}^i B_{k,l}(S_I, S_{II}, y^I, y^{II}) \qquad (2)$$

Where, n , and , m , are spline order and number of knots, respectively and $a_{k,l}^i$ are unknown parameters which should be estimated. The function $B_{k,l}(S_I, S_{II}, y^I, y^{II})$ is the B-spline basic function determined by the spline order (m) and extended partition vector, y^i. A key advantage of these functions is the degree of control over the shape of kr curves that can be produced. In other words, many different shapes of relative permeability curves can be easily provided by Spline function using few knots.

Estimation procedure

Determination of the coefficients within the B-spline representation is carried out by Genetic Algorithm (GA). An objective function is formulated as a sum of squared difference between the measured data and corresponding values calculated from the mathematical model of the experiment.

With appropriate choice of mathematical model and unknown coefficient ($a_{k,l}^i$), maximum-likelihood estimates are obtained. Generally, it can be taken to be a diagonal matrix with entries equal to the inverse of the estimated variances of data measured errors.

VERIFICATION OF THE ALGORITHM

To validate the integrity of the developed 3-phase coreflood simulation, synthetic core flood data were generated and used. Core and fluid properties and three-phase kr were used to generate synthetic experimental data including production and pressure data by numerically simulating a SWAG (simultaneous water and gas injection) experiment using Eclipse 100 simulator. The core properties used in this simulation (Table.1) were the same as the core used in the laboratory to perform real experiments. The oil-gas Pc (capillary pressure) was assumed to be negligible whereas the oil-water Pc was used in the simulation. Water and gas were simultaneously injected at an equal rate (100 cm^3/hr) through the core with an initial oil saturation of 92% and a connate water saturation of 8%. To perform numerical simulation of the experiment, synthetic three-phase kro, krw and krg were generated as 2D table using SOF32D, SWF32D and SGF32D keywords in Eclipse100.

The simulated values of oil recovery and pressure drop across the core versus PV (pore volume) injected were then imported as input data into our history matching software to estimate the oil, water and gas relative permeability values. In other words, our programme back calculated unknown relative permeabilities from fluid recovery and pressure drop data. Generic Algorithm (GA) started with 20 populations then crossover and mutation procedure were implemented via 200 iterations to reach a global minimum value of misfit.

Comparison of the oil recovery for synthetic data (generated by Eclipse simulator) and the history matched results obtained by our program are shown in Figure 1. Estimated and real kr of oil, water and gas are shown in Figure 2 to Figure 4. These Figures show that for the range of average saturation (obtained by volumetric balance calculation) involved in this experiment the kr values obtained from our program are in good agreement with the input kr values to ECLIPSE for this SWAG experiment.

COREFLOOD EXPERIMENT

Having verified the integrity of the coreflood simulator as explained above, the kr estimation approach was then successfully applied to a coreflood experiments carried out under three-phase flow conditions to obtain three-phase relative permeability for oil, water and gas. The experiment was conducted on a mixed-wet core as described in Table.1. Table 2 shows the measured properties of the fluid system at the conditions of the experiments.

Gas injection

Having saturated the mixed-wet core with 60% oil and 40% water at 1840 psia, gas injection was carried out at 200 cm^3/hr. The experiment stopped after injecting around 1 PV of gas.

The data required for simulation of this experiment are the capillary pressure as well as the experimental data such as the profiles of the pressure drop across the core and also the produced volume of oil, gas and water during the experiment. Due to the low interfacial tension between the oil and gas (0.04 mN/m) used in this experiment, the capillary forces between the oil and gas were assumed to be negligible while the oil-water capillary pressure was accounted for. Relative permeability of each phase is assumed to be a function of two independent saturations (i.e. kro = kro (Sw, Sg), krw = krw (So, Sg), krg = krg (Sw, So)). The unknown three-phase kro, krw and krg are then calculated by minimizing the difference between the simulated and the measured recovery and pressure drop data. The history matched and the measured oil production and pressure drop are shown in Figure 5 and Figure 6 respectively. As can be seen, there is a good agreement between the history-matched and the laboratory data. The estimated kr values are given in Figure 7 to Figure 9.

Having obtained 3-phase kr curves for the experiment, the experiment was numerically simulated using Eclipse 100 by importing the estimated kr data to verify the accuracy of the estimated 3-phase kr values. The good agreement observed between the Eclipse results and the corresponding measured and history matched results are given in Figure 5 and Figure 6 demonstrating the high accuracy of the estimated kr data.

CONCLUSIONS

The following conclusions can be drawn from the methodology presented in this paper:

1- A powerful tool has been developed to accurately estimate three-phase kr from experimentally measured production and pressure drop of unsteady state coreflood displacement tests. An appropriate and flexible function was chosen for three-phase relative permeability to generate a wide range of relative permeability curves by obtaining a minimum misfit value in an optimization process. Estimated kr values by this approach are more accurate in the vicinity of the saturation trajectory in which the experiment occurred

2- To overcome one of the limitations assumed in most of the existing kr models regarding dependency of krw and krg to only their own saturation (i.e. krw = krw (Sw), krg = krg (Sg)), we considered three-phase krw and krg as a function of two saturations (krw = krw (So, Sg), krg = krg (So, Sw)) as well as the three-phase oil relative permeability.
3- By applying the new algorithm we can overcome some the restrictions present in the JBN explicit method such as neglecting capillary forces.
4- The presented history matching approach was successfully verified by synthetic data built by Eclipse simulator.
5- Estimated kr values obtained from history matching of coreflood experiments were successfully verified by using these kr to simulate corresponding experiment by Eclipse.

ACNOWLEDGMENT

This work was carried out as part of the Water-Alternating-Gas (WAG) Injection JIP at Heriot-Watt University. The WAG consortium at Heriot-Watt University is equally sponsored by, *Statoil, BHP Billiton, Chevron, Dong Energy, Petrobras and the UK Department of Energy and Climate Change (DECC)*, which is gratefully acknowledged.

REFERENCES

1. Bard, Y.: "Nonlinear parameter Estimation", *Academic Press Inc*., Washington, DC (1974).
2. Johnson, E. F., D. P. Bossler, and V. O. Naumann, "Calculation of relative Permeability from Displacement experiments," *Trans. AIME*, 370 (1958).
3. Kerig, P.D. and Watson, A.T.: "Relative permeability Estimation from Displacement Experiments: An Error Analysis,"*SPERE (1986)* 175-82; Trans., AIME, 281
4. Mejia.G.M., A.T. Watson, and J.E. Nordtvedt, "Estimation of three-phase flow functions in porous media", *AIChE* Journal (July 1996).
5. Richmond, P.C, : "Estimation Multi-Phase Flow Function in Porous Media From Dynamic Displacement experiments", "PhD dissertation, *Texas A&M U*., College Station, TX (1988)"

Table 1. Core properties

Length (cm)	61.3
Diameter (cm)	4.86
Pore volume (cc)	200
Porosity(%)	17.7%
Absolute Permeability(md)	1000
Swi(%)	8%

Table 2:Fluid properties at 1840psia and 37.8C

Properties	Oil	Gas	Water
Density (g/cc)	0.317	0.211	0.98
Viscosity (cp)	0.0405	0.0249	0.68
Interfacial tension (mN/m)	Oil/gas = 0.04		

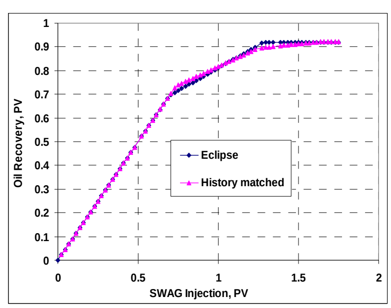

Figure 1: Oil recovery versus injected fluid of synthetic SWAG test obtained from Eclipse and history matching.

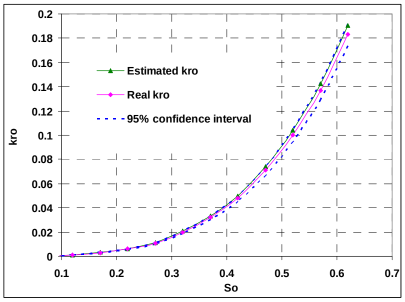

Figure 2: Estimated and real three-phase oil relative permeability at Sw = 0.3 for synthetic SWAG experiment

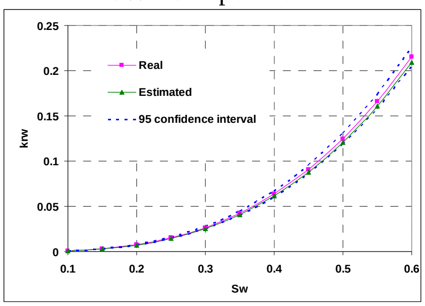

Figure 3: Estimated and real three-phase water relative permeability at Sg = 0.3 for synthetic SWAG experiment

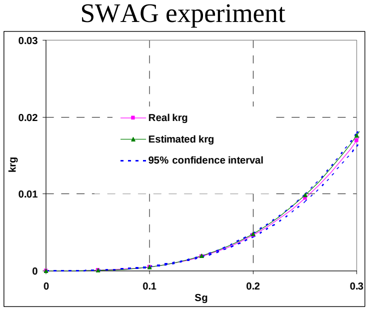

Figure 4: Estimated and real three-phase gas relative permeability at Sw = 0.20 for synthetic SWAG experiment

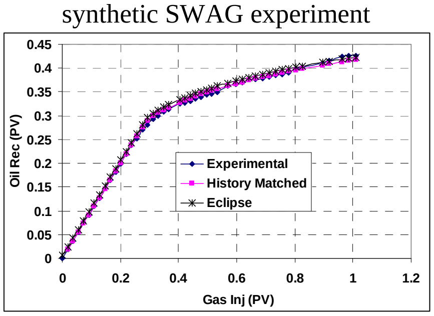

Figure 5: History matched, eclipse simulation and measured oil production of Gas injection experiment

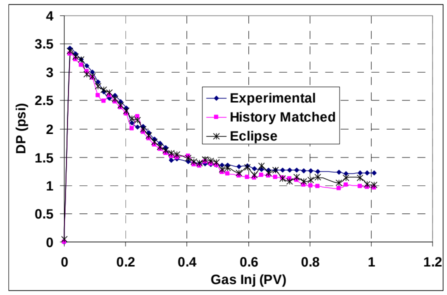

Figure 6: History matched, eclipse simulation and measured pressure drop across the core of Gas injection experiment

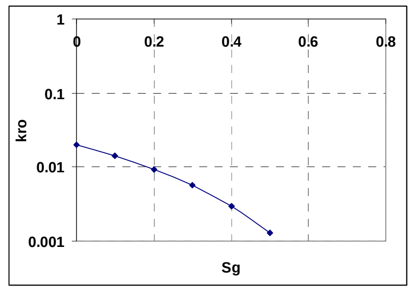

Figure 7: Estimated oil kr from gas injection at Sw=40%.

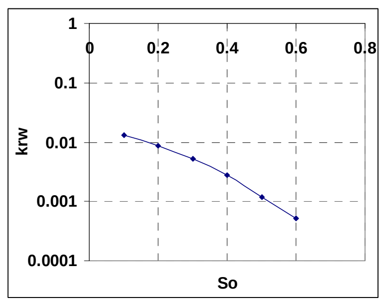

Figure 8: Estimated water kr from gas injection at Sg=20%.

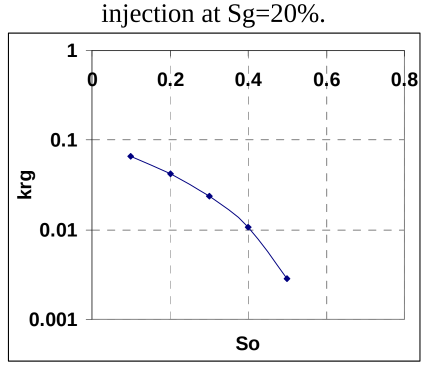

Figure 9: Estimated gas kr from gas injection at Sw=40%.