# A Capillary Pressure Function for Interpretation of Core-Scale Displacement Experiments

X.D. Jing and J.N.M. van Wunnik*
Centre for Petroleum Studies, Imperial College, UK
* Shell International E&P - RTS, The Netherlands

## Abstract

A capillary pressure function is proposed for interpreting core-scale flow experiments. This function has been found suitable for a wide range of rock/fluid systems with different pore geometry and wettability characteristics. The petrophysical controls are reflected in the asymptotic values relating to irreducible saturation, and threshold capillary pressure, and in the shape parameters relating to the pore throat size distribution.

This function works in both drainage and imbibition modes. When combined with a relative permeability model such as the Corey model, the same residual oil saturation value can be used in both the capillary pressure and the relative permeability functions. Examples are given to illustrate its application in interpreting oil/water multi-speed centrifuge experiments on a range of reservoir cores including high permeability sandstone rocks of intermediate wettability, as well as carbonate reservoir rocks. This paper also assesses the uncertainty of residual oil saturation, oil relative permeability and imbibition capillary pressure obtained from multi-speed centrifuge experiments using a numerical simulator.

## Introduction

Capillary pressure ($P_c$) is defined as the pressure difference across a curved interface between two immiscible fluids. For oil/water systems in porous rock, $P_c$ is generally defined as the pressure difference between the oil phase ($P_o$) and water phase ($P_w$), *i.e.*, $P_c = P_o - P_w$, and expressed as a function of water saturation ($S_w$) (Amyx et al., 1960).

$P_c$ reflects the interaction of rock and fluids, and so is controlled by the pore geometry, interfacial tension and wettability. In reservoir engineering, $P_c$ is a basic input for simulation studies, and its effect on oil recovery can be especially significant for heterogeneous systems. In petrophysical evaluation, $P_c$ is also an important parameter, e.g., for calculating field-wide water-saturation versus height relationships from core and log information. Both imbibition and drainage capillary pressure curves may be required for field studies, depending on the field saturation history. In order to avoid ambiguity, in this paper we define imbibition as increasing water saturation, and drainage as increasing oil saturation, irrespective of the wettability situation. There are various laboratory techniques available for generating $P_c$ curves, e.g., porous-plate equilibrium, mercury injection and centrifuge techniques. However, conventional techniques suffer from drawbacks such as lengthy test duration, unrealistic wettability situation, as well as experimental and interpretation difficulties (Amyx et al., 1960).

Core-scale displacement experiments (steady-state, unsteady-state and centrifuge experiments) are performed primarily for the purpose of generating relative permeability curves. The interpretation of flow experiments has traditionally been based on analytical techniques, without necessarily taking into account the actual flow processes, boundary conditions and sample heterogeneity. For example, the interpretation of multi-speed centrifuge experiments for capillary pressure often assumes capillary/centrifuge force equilibrium and centrifugal acceleration being constant over the core (Hassler and Brunner, 1945). The Hagoort (1980) analysis for relative permeability from a single-speed centrifuge experiment is only valid under the assumption of zero capillary pressure, zero viscosity of the invading phase, instantaneous start-up, and constant centrifugal acceleration over the core. In reality, capillary pressure and relative permeability effects are often coupled in a single flow experiment, and their separation requires the use of a numerical simulator (Archer and Wong, 1973; Sigmund and McCaffery, 1979 and Tao and Watson, 1984).

To solve for capillary pressure and relative permeability numerically from two-phase flow experiments, certain forms of capillary pressure and relative permeability functions are often assumed. The chosen functions should offer flexibility, and yet honour pore geometry and wettability controls as well as general experimental trends. They should be capable of describing the petrophysical characteristics of a wide range of reservoir rocks, and to cover a range of wettability characteristics, particularly intermediate wettability.

We studied a number of existing capillary pressure functions including Lambda (Brooks-Corey, 1964), van Genuchten (1980) and a modified version (Lenhard and Oostrom, 1998), Thomeer (1983), as well as Polynomial, Sigmoidal, Exponential (e.g., Skelt and Harrison, 1995) and Hyperbolic functions. These functions have been found useful for describing saturation-height (i.e., $P_c$) relationships in specific field cases, but they may suffer from limitations such as poor matches of threshold pressure and irreducible/residual fluid saturation, as well as inability to model a sharp capillary transition. For reservoir rock/fluid systems with intermediate wettability and high permeability, a sharp capillary transition both in drainage and imbibition is often observed. This presents a problem for most of the above mentioned functions.

We propose a new $P_c$ function and demonstrate its application for interpreting centrifuge experiments using a numerical simulator, MoRes. This capillary function offers flexibility for describing a wide range of rock/fluid systems including high permeability and intermediate wetting behaviour, and tight carbonate reservoir rocks. It also honours petrophysical controls in the asymptotic values relating to irreducible saturation and threshold capillary pressure ($P_{ct}$) and the shape parameters relating to pore throat size distributions. In addition, the same $S_{or}$ and $S_{wc}$ can be used in both the $P_c$ function and the Corey $K_{ro}$ function, thus ensuring consistency and providing a better definition of $S_{or}$, which corresponds to $K_{ro} = 0$ and $P_c \rightarrow -\infty$ in the imbibition cycle.

## The capillary pressure function

We propose the following functional form for capillary pressure curves:

$$P_c = P_c{}^o\left[\left(\frac{d}{S-S'}\right)^n + a\right]; \qquad (1 > S > S') \qquad (1)$$

where ,

$P_c{}^o$ is the capillary pressure scaling factor,

*S, S'* are mobile and irreducible saturation fractions, respectively,

*d* defines the curvature and controls the distance, *f(d)*, from the inflexion point to the intersection of the two asymptotic lines,

*n* is the asymmetry shape factor, and for most cases *n* can be set as 2,

*a* controls the value of threshold $P_c$.

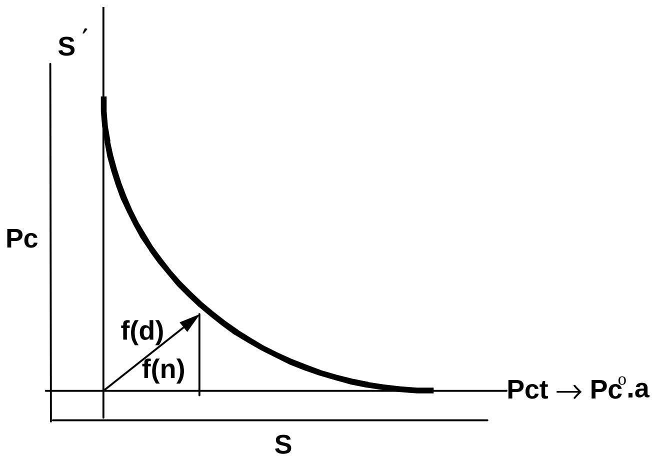


Figure 1 Schematic illustration of the capillary pressure function showing the parameters.

For a water/oil system in the *imbibition* cycle (i.e., increasing water saturation), the above capillary pressure equation can be written as:

$$P_c(S_w) = P_c{}^o\left[\left(\frac{d}{1-S_w-S_{or}}\right)^n + a\right]; \qquad (1 > 1-S_w > S_{or}) \qquad (2)$$

where, $S_w$ is the water saturation fraction, and $S_{or}$ is the residual oil saturation fraction.

For a water/oil system in the *drainage* cycle (i.e., increasing oil saturation), the capillary pressure equation can be written as:

$$P_c(S_w) = P_c{}^o \left[ \left( \frac{d}{S_w - S_{wc}} \right)^n + a \right]; \qquad (1 > S_w > S_{wc}) \qquad (3)$$

where $S_{wc}$ is the connate water saturation fraction. The values of $P_c{}^o$, $d$ and $a$ in the drainage cycle are different from those in the imbibition cycle.

The residual oil ($S_{or}$) and connate water ($S_{wc}$) in the above $P_c$ equations must be consistent with those in relative permeability models such as Corey (1954):

$$K_{ro(Sw)} = K_{ro(Swc)} \left( \frac{1 - S_w - S_{or}}{1 - S_{wc} - S_{or}} \right)^{n_o} \qquad (4)$$

$$K_{rw(Sw)} = K_{rw(Sor)} \left( \frac{S_w - S_{wc}}{1 - S_{wc} - S_{or}} \right)^{n_w} \qquad (5)$$

where $K_{ro}$ and $K_{rw}$ are the oil and water relative permeability, respectively, $S_{wc}$ is the connate water saturation, and $n_o$ and $n_w$ are the Corey exponents for oil and water, respectively.

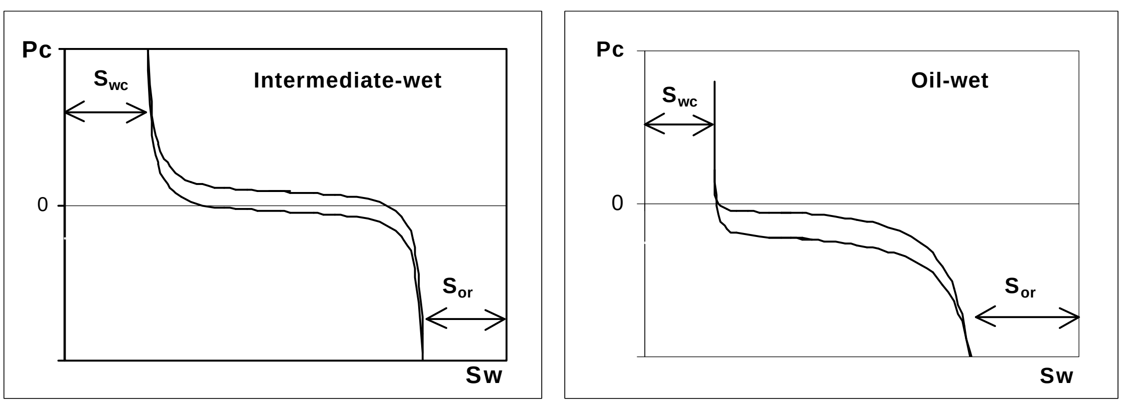


Figure 2 The full capillary curve for intermediate-wet and oil-wet conditions. The curves are generated from the Pc function (Eqn. 1-3).

Sandstone oil-zone reservoir rock is usually found to be intermediate-wet, i.e., some pore surfaces are water wet and others are oil wet, whereas oil-zone carbonates are believed to be more oil-wet than clastics. Figure 2 gives examples of the full capillary pressure loops for rocks of intermediate-wet and oil-wet characteristics. The curves shown in Figure 2 are generated from the capillary pressure function (Eqn. 1-3), with each full loop corresponding to four sets of $P_c$ function parameters (i.e., covering forced and spontaneous drainage and ambition). Figure 3 shows sets of forced imbibition capillary pressure curves in order to illustrate the effects of altering the parameters involved in the $P_c$ function. In addition to the effect of theoretical residual oil saturation ($S_{or}$), Figure 3 shows the influence of $a$ in controlling the threshold $P_c$ and the cross-over point from spontaneous to forced ambition, $d$ and $n$ in controlling the shape of the $P_c$ curves, and $P_c^o$ itself for scale-up. In most centrifuge cases $a$, $d$ and $n$ can be fixed at optimum values based on approximation from the Hassler-Brunner solution, assuming static equilibrium. $n$ can be set at a default value of 2 for most cases.

## Multi-speed centrifuge experiments

The centrifuge technique is a displacement method, which relies on the centrifugal force across the plug. During the experiment, a core plug is saturated with one (or two) phases and spun around in a core holder that is filled with the other phase. The production of the phase expelled from the core plug by the centrifugal force is measured as a function of time. Both imbibition and drainage experiments can be performed to determine capillary pressure and relative permeability curves. Conventionally, single-speed experiments are carried out at a single, fixed centrifugal acceleration for determining the relative permeability of the expelled phase. Multi-speed experiments are carried out at a series of fixed centrifugal accelerations to reach static equilibrium for capillary pressure measurements. In practice, analytical centrifuge models such as the Hassler-Brunner (1945) and other improved versions (e.g., Ruth and Chen, 1995, for a review), and the Hagoort (1980) analysis for relative permeability are often inadequate for describing the flow processes. This is because long equilibrium times may be needed at small relative permeability values, whereas on the other hand, capillary forces may hold up the expelled phase at the outlet and generally influence the flow process. Therefore, numerical simulations are required to separate the role of capillary pressure and relative permeability in the centrifuge and other displacement experiments.

To demonstrate the use of the $P_c$ function for determining the imbibition capillary pressure and oil relative permeability of core plug samples, multi-speed centrifuge experiments were performed and simulated. Prior to the centrifuge experiments, the sandstone sample set under study was carefully selected based on visual examination and SEM studies to identify the presence of hairy clays (illites), which are known to irreversibly disturb the core plug characteristics during routine cleaning. If clays are present, a special cleaning method, e.g., critical point drying, may be required. All sandstone plugs were thoroughly cleaned in a hot toluene extraction (Soxhlett) followed by a hot azeotropic chloroform/methanol/water mixture, and then dried in a vacuum oven. These plugs were CT-scanned to detect the degree of heterogeneities. After visual and statistical analysis of the CT-data, around 25% of the total plugs were selected for the special core analysis. The original sample wettability believed to be representative for the reservoir was then restored by ageing the samples in dead crude and artificial formation brine at reservoir temperature for three weeks. Centrifuge experiments were then performed on the sandstone and carbonate samples. The procedure and discussion on measurement accuracy of multi-speed centrifuge experiments can be found elsewhere (e.g., Ruth and Chen, 1995).

Table 1 List of rock/fluid properties

| | Unit | JS1 | S3 | S30 | QA |
|---|---|---|---|---|---|
| core length | Cm | 3.01 | 5.01 | 4.81 | 3.61 |
| Core area | $cm^2$ | 11.02 | 10.24 | 11.40 | 7.79 |
| $K_{air}$ | MD | 227 | 924 | 1624 | 4.0 |
| Porosity | -- | 0.261 | 0.308 | 0.296 | 0.300 |
| oil density | $Kg/m^3$ | 860.2 | 781.0 | 781.0 | 727.0 |
| water density | $Kg/m^3$ | 1002 | 1023 | 1023 | 1165 |
| oil viscosity | Pa.S | 7.50E-03 | 2.27E-03 | 2.27E-03 | 9.20E-04 |
| water viscosity | Pa.S | 9.70E-04 | 1.04E-03 | 1.04E-03 | 9.28E-04 |
| IFT | mN/m | 15 | 26 | 26 | 30 |

Table 1 summaries the basic rock and fluid properties of four samples (JS1, S3, S30, QA). JS1, S3 and S30 are sandstone samples, whereas QA is from a tight carbonate reservoir in the Middle East. The samples contain only minor amounts of clay. The data were simulated using MoRes with the Pc function (Eqn.1-3) and Corey models.

## Simulation of centrifuge displacement

To overcome the limitations of the analytical methods and unravel the role of capillary pressure and relative permeability, numerical simulation models have been developed for interpreting centrifuge experiments. In this study, multi-speed centrifuge experiments were interpreted based on the Shell Group reservoir simulator, MoRes, which is a fully implicit, 3-D reservoir simulator for compressible, multi-component, multi-phase flow.

The following input data are required for the simulation: (1) various centrifuge speeds corresponding to accelerated gravitational forces in increasing steps, (2) cumulative production and average saturation data against time, (3) rock and fluid properties, and core/centrifuge geometrical information, and (4) numerical model definition (i.e., number of grids and boundary conditions reflecting the actual experiments). The relative permeability tables for both phases and the capillary pressure data in the appropriate direction are also required as input. The iterative process starts with an initial guess of the $K_r$ and $P_c$ functions and then the simulation is run and the predicted production data compared against the actual experimental measurements. In the manual mode, the $K_r$ (only for the expelled phase) and $P_c$ curves are adjusted each time after a new simulation run until an acceptable match between the prediction and laboratory data is achieved. In order to obtain a match more quickly, the initial input of capillary pressure curve can be approximated from the Hassler-Brunner equation, assuming hydrostatic equilibrium. The initial estimation of residual oil saturation is from material-balance calculations.

## Results and discussion

The data for the four samples JS1, S3, S30, QA as listed in Table 1 were used in the simulation study using MoRes. The new capillary pressure function and Corey models were used to generate input tables in an iterative manner. Figures 4-7 show the simulation match of multi-speed centrifuge data and the final capillary pressure and oil relative permeability for the four reservoir cores. A close match between the experiment and the simulation was found in all cases. Table 2 lists the final output values of the parameters in the $P_c$ and $K_r$ functions.

Table 2 List of parameters in Pc and Kr functions after matching experiments

| Pc function Parameters | JS1 (Sandstone) | S3 (Sandstone) | S30 (Sandstone) | QA (Carbonate) |
|---|---|---|---|---|
| $P_c^o$ (bar) | 3.25 | 2.90 | 2.90 | 0.90 |
| $S_{or}$ | 0.09 | 0.20 | 0.27 | 0.15 |
| *d* | 1.12E-02 | 3.95E-03 | 4.65E-04 | 1.18E-01 |
| *n* | 2.0 | 2.0 | 2.0 | 2.0 |
| *a* | 2.0E-03 | 1.55E-03 | 1.22E-03 | 7.0E-01 |
| $n_o$ *(Corey exponent)* | 4.0 | 3.0 | 3.0 | 4.0 |

Experience has shown that in most centrifuge cases *a*, *d* and *n* can be fixed at optimum values based on approximation from the Hassler-Brunner solution, assuming static equilibrium. *n* can be fixed at 2 for most cases. Only residual oil ($S_{or}$), capillary pressure scaling factor ($P_c^o$) and the Corey oil exponent ($n_o$) need to be found iteratively by history-matching the dynamic multi-speed data. This avoids the much more mathematically complex case of simultaneously optimizing all the parameters.

It is interesting to note that the values of $S_{or}$ for some of the samples are significantly lower than the expected values (i.e., from conventional special core analysis). This is due to the theoretically correct definition of $S_{or}$ and the consistency in simulation of the experimental data. Kokkedee et al. (1996) reported that the scope for lower residual oil saturation, based on the numerical interpretation of data from special core analysis, could be 10% in saturation or more. One may argue that such low values of $S_{or}$ may never be achieved in any part of a reservoir. But the use of the correct $S_{or}$ value in $P_c$ and $K_r$ tables leads to better characterisation of two-phase flow, and improved prediction of remaining oil distribution and reservoir performance.

Table 3 Sensitivity study

| Parameters | Sensitivity |
|---|---|
| $S_{or}$ | ± 0.02 (in fraction) |
| $P_c$ values | ± 10% |
| Corey oil exponent ($n_o$) | ± 10% |

A series of sensitivity studies were carried out based on the new $P_c$ function and the Corey $K_r$ function with a focus on the sensitivity of $S_{or}$. Table 3 lists the sensitivities of the three key parameters. The criterion is that the prediction of oil production must be within the same acceptable tolerance.

## Conclusions

We have developed a capillary pressure function (eqn.1-3) for interpreting multi-speed centrifuge experiments. This function offers flexibility for a wide range of rock/fluid systems and yet honours key petrophysical controls. Based on a combination of the Pc function and the Corey relative permeability model, we demonstrate a procedure for defining residual oil saturation from special core analysis.

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