ABSTRACT

Spuriously high water saturation has often been computed in hydrocarbon bearing reservoirs with low formation resistivity, resulting in underestimation of hydrocarbon resources. One common approach to overcome this problem is to use capillary pressure data from cores. Although technically sound, its main drawback is that most wells often lack appropriate core data. This paper proposes that generic capillary pressure curves generated using core data from typical sandstone reservoirs can be used to compute water saturation in other similar sandstone reservoirs from different fields, areas or regions. This is based on the assumption that sandstone reservoirs having similar Rock Quality Index (RQI) and wetability, will exhibit similar capillary pressure behavior with respect to the water saturation. Generic capillary pressure curves have been generated using actual core data from several wells in Malaysia. Empirical relationships were established between curve fitting parameters and RQI values of the core plugs. The generic capillary pressure curves were then used to compute water saturation in other wells, which do not have core data. The pseudo RQI values for these wells were computed using the log derived porosity and permeability. With these pseudo RQI values and height above the Free Water Level, a water saturation equation was derived, as a function of RQI and height. The results have been verified in test wells, which have their own core data. In wells without core data, water saturation derived from generic capillary curves was compared with that computed from resistivity logs. These water saturation values were found to be more realistic than those computed from resistivity logs alone. Well test results, where available, also confirmed the validity of the method used and the reliability of the computed water saturation. The results from these experiments confirmed the assumption that the generic capillary pressure curves can be used to predict water saturation in wells without core data.

INTRODUCTION

Water saturation computation is a crucial and integral part of any petrophysical evaluation. Water saturation \( S_w \) calculated using resistivity logs is still the preferred standard method in the oil and gas industry. Spuriously high water saturation has often been computed in hydrocarbon bearing reservoirs with low formation resistivity. In thinly laminated sands or so called Low Resistivity Low Contrast pay sands, the water saturation based on resistivity logs usually tends to be pessimistic. This has invariably resulted in underestimation of hydrocarbon resources. Over the years several methods have been developed to overcome this problem. Some of them are relatively simple and some more complicated, involving resistivity modeling based on resistivity imaging tools or by deploying sophisticated resistivity logging tools such as the Triaxial Induction Resistivity tool. The results have been somewhat mixed. Another common approach is to use capillary pressure data from core analysis. Although this has a sound technical basis, its main drawback is that most wells often do not have appropriate core data. Several papers have been written on this subject and methods described to derive resistivity-independent water saturation based on capillary pressure data. In this paper, it is proposed that generic capillary pressure curves generated using core data from several typical sandstone reservoirs can be used to compute water saturation in other similar sandstone reservoirs from different fields, areas or regions. This is based on the assumption that sandstone reservoirs, which have similar “Rock Quality Index or RQI”, expressed by the square root of the ratio of absolute permeability and porosity, will exhibit similar capillary pressure behavior with respect to the wetting phase saturation, namely water saturation. The authors have produced generic capillary pressure curves based on actual core data from several wells in Malaysia. Skelt-Harrison method is used to perform curve fitting on the measured capillary pressure curves. Empirical relationships are then established between the curve fitting parameters and the RQI values of these core plugs. Based on these empirical relationships, generic capillary curves are produced. These generic capillary pressure curves are then used to compute water saturation in other wells, which do not have core data. The pseudo RQI values for these wells can be generated using the log derived porosity and permeability, computed either from suitable porosity-permeability transforms or empirical equations. Based on these pseudo RQI values and “Height above the Free Water Level”, a water saturation \( S_w \) curve is generated. The resulting water saturation,
computed from the generic capillary pressure curves, has been verified in test wells, which have their own core data. In other wells, without core data, the water saturation derived from generic capillary pressure curves has been compared with that computed from resistivity logs. The water saturation values, derived from the generic capillary pressure curves, were found to be more realistic than those computed from resistivity logs alone. Well test results, available in some of the wells, also confirmed the validity of the method used and the credibility of the computed water saturation. The results from this study demonstrate that generic capillary pressure data can be used to compute water saturation in sandstone reservoirs for different fields, areas or regions, provided that the RQI values of these reservoirs are similar to those from the wells where the core data was taken. A Saturation Height Function has also been built based on these generic capillary pressure curves. This Saturation Height Function has been used successfully to distribute water saturation in geo-cellular models and reservoir dynamic models for several oil and gas fields operated by PETRONAS Carigali Sdn. Bhd.

**OBJECTIVE**

To develop a method which can be used to compute water saturation independent of resistivity logs. This will give an estimation of water saturation based on the displacement of formation water by hydrocarbon during the drainage cycle of hydrocarbon migration. Water saturation estimated using this method will be more representative of the actual formation water saturation based on resistivity logs, thereby leading to better estimation of hydrocarbon resources.

**PROPOSED METHODOLOGY**

Drainage cycle capillary pressure data of several core plugs were chosen from selected wells in the Malay Basin, offshore Malaysia. Quality check was performed to validate the capillary pressure data from these core plugs. Curve fitting of each capillary curve was performed using the Skelt-Harrison method, whereby curve fitting parameters $a_1$, $a_2$, $a_3$ and $a_4$ were computed. Correlations between these constants and RQI (Rock Quality Index) of the core plugs were established and equations for these constants as a function RQI were obtained. Synthetic capillary pressure curves can then be created based on these equations, thereby relating the water saturation $S_w$ as a function of $P_c$ (capillary pressure), RQI (Rock Quality Index) and Interfacial Tension of the rock at any depth above the Free Water Level. This Saturation Height Function allows the estimation of $S_w$ at any depth above the Free Water Level in the field depending on the RQI of the reservoir rock at that depth. It provides an equation for water saturation $S_w$ as a function of capillary pressure $P_c$, Rock Quality Index RQI and interfacial tension between water and hydrocarbon in the reservoir rock. The capillary pressure at any height above the Free Water Level in the reservoir can be computed using the pressure gradients of water and hydrocarbon. RQI is computed from the log derived porosity and permeability or using a suitable porosity-permeability relationship derived from core data, when available. Industry standard values of Interfacial Tension and Contact Angle can be used for appropriate hydrocarbon type; to convert the laboratory measured capillary pressure curves (which have been used to derive the Saturation Height Function) to reservoir conditions. An appropriate pair of water and hydrocarbon type should be used for the conversion to reservoir conditions.

**PROCEDURE**

After carrying out quality check on available core data, ten capillary pressure curves were chosen to cover a wide range of Rock Quality Index (RQI) in different types of reservoirs. These capillary pressure curves are then used to build the water saturation model.

Using the Skelt-Harrison capillary pressure equation (Eqn.1), curve fitting operation was performed to determine the curve fitting parameters $a_1$, $a_2$, $a_3$ and $a_4$. Since there are ten capillary pressure curves, ten different values of $a_1$, $a_2$, $a_3$ and $a_4$ were obtained.

**Water saturation computation using $P_c$ data**

Water saturation $S_w$ can be computed from $P_c$ using the following equation (Eqn.1):

$$SW_{SKELT} = \frac{100 - a_1 e^{\frac{(a_2)^3}{P_c - a_3}}}{100}$$

Where: $a_1$, $a_2$, $a_3$ and $a_4$ are curve fitting parameters (see Figure 2)

**Rock Quality Index (RQI) computation**

The RQI of the reservoir rock can be computed using the following equation (Eqn.2):

$$RQI = \frac{K}{\Phi^{\frac{1}{2}}}$$

Where: $RQI$ = Rock Quality Index  
$K$ = Permeability in md  
$\Phi$ = Porosity in decimal fraction
Curve fitting parameters as a function of RQI

Draw crossplots for all $a_1$ values vs RQI and obtain an equation for $a_1$ as a function of RQI. Do the same for $a_2$, $a_3$ and $a_4$ values as follows:

$$a_1 = b_1 \cdot \ln(RQI) + c_1$$
$$a_2 = b_2 \cdot \ln(RQI) + c_2$$
$$a_3 = b_3 \cdot \ln(RQI) + c_3$$
$$a_4 = b_4 \cdot \ln(RQI) + c_4$$

Where: $b_1$, $b_2$, $b_3$, $b_4$, $c_1$, $c_2$, $c_3$ and $c_4$ are constants derived from appropriate crossplots relating curve fitting parameters as a function of RQI (see Figures 4 to 7).

Capillary pressure computation in the reservoir

At any point in the hydrocarbon bearing reservoir, a capillary pressure can be computed using the following equation (Eqn.3):

$$P_c = (g_w - g_h) \cdot H$$

Where:
- $P_c$ = Computed capillary pressure (psi)
- $g_w$ = Pressure gradient of water (psi/ft)
- $g_h$ = Pressure gradient of hydrocarbon (psi/ft)
- $H$ = Height above Free Water Level (feet)
- $H = (FWL – Depth)$ in feet

By substituting this $P_c$ formula into Eqn.1 and replacing the parameters $a_1$, $a_2$, $a_3$ and $a_4$ with their appropriate equations, the Skelt-Harrison water saturation equation (Eqn.1) will now become an $S_w$ equation as a function of height above FWL and RQI of the reservoir rock.

UNDERLYING CONCEPT

Sandstone reservoirs with similar RQI (expressed as the Square Root of $K/\Phi$) and wettability will exhibit similar capillary pressure behavior with respect to the wetting phase saturation, namely water saturation. Therefore, the Saturation Height Function derived from the core plugs taken from the Malay Basin, offshore Malaysia, can be used to predict water saturation in similar sandstone reservoirs in other fields, regions or areas.

PROOF OF CONCEPT

The Saturation Height Function developed based on generic capillary pressure curves, using the method outlined above, has been tested in many wells, both in Malaysia as well as overseas. The results have been verified in test wells, which have their own core data. In wells without core data, water saturation derived from generic capillary curves was compared with that computed from resistivity logs. These water saturation values were found to be more realistic than those computed from resistivity logs alone. Well test results, where available, also confirmed the validity of the method used and the credibility of the computed water saturation. The results from these experiments confirm the assumption that generic capillary curves can be used to predict water saturation in wells without core data.

This saturation height function has been tested and used to compute water saturation in several geocellular static models for Full Field Reviews and Field Development Plans. It has also been used successfully in reservoir simulation models for the same fields. Hence PETRONAS Carigali has adopted this Saturation Height Function to be used to compute water saturation independent of resistivity logs.

Figures 9 to 16 illustrate the comparison between the $S_w$ computed from resistivity logs and the $S_w$ derived from generic capillary pressure curves, in several test wells. It can be seen that the $S_w$ from generic capillary pressure curves is either similar or more optimistic than $S_w$ from resistivity logs. The solid curve is $S_w$ from resistivity logs and the dashed curve $S_w$ from generic capillary pressure curves. These examples indicate that the saturation height function works well in both gas and oil bearing reservoirs from several different fields in Malaysia, Myanmar and Egypt.

IMPACT OF WATER SATURATION

Accurate computation of water saturation $S_w$ will result in better estimation of hydrocarbon volumes, leading to more reliable assessment of the oil or gas field. This will have a big impact on the economic viability of a project. A robust Saturation Height Function will result in more accurate geo-cellular and reservoir simulation models. This will subsequently lead to better prediction of production forecast, reservoir management plan and monetization scheme for the field. Therefore, substantial amount of revenue, in terms of millions of dollars, can be generated by proper and accurate estimate of water saturation using this Saturation Height Function.

CONCLUSION

The results from the experiments conducted in this study confirm the assumption that sandstone reservoirs with similar RQI and wettability will exhibit similar capillary pressure behavior with respect to the water saturation. Hence generic capillary pressure curves created using capillary pressure data from a cored well can be used to predict water saturation in wells without core data, provided that the sandstone reservoirs have similar rock quality index.
FIGURES

Figure 1: Selected capillary pressure curves

Figure 2: Curve fitting parameters controlling the shape of a capillary pressure curve.
(a1 controls the irreducible water saturation, a2 and a3 control the curvature and a4 controls the entry height pressure)
Note: a1, a2, a3 and a4 are obtained by using the “Equation Solver” function in spreadsheet software.

Figure 3: Correlation between actual and reconstructed water saturation curves

Figure 4: $a_1 = f(K, \Phi)$

Figure 5: $a_2 = f(K, \Phi)$
Figure 6: $a_3$ vs RQI plot, $a_3 = f(RQI)$

Figure 7: $a_4$ vs RQI plot, $a_4 = f(RQI)$

Figure 8: Comparison of Sw from capillary pressure and Sw from Waxman Smits equation

Figure 9 - Field-A, Well: A01, Location- Malaysia

Figure 10 - Field: B, Well: B01, Location: Malaysia
Figure 11 - Well: C01, Location: Malaysia

Figure 12 - Field: D, Well: D01, Location: Malaysia

Figure 13 - Well: E01, Location: Myanmar

Figure 14 - Well: F01, Location: Myanmar
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