Log Derived Saturation Functions for Giant Carbonate Reservoirs in the Middle East

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Abstract: Fluid saturation distribution at initial reservoir conditions is vital for calculation of original oil in place (STOOIP) and reservoir simulation (dynamic models). It is a critical step in model initialization, since the subsequent step (quality of history matching) is largely dependent on the initial fluid distribution at time zero.

In many reservoirs there are limited or no SCAL (drainage capillary pressure) data available and in many cases, the available limited SCAL data has poor quality and subjective plug selection. However, log-data (open hole logs, OHL) and routine core analysis (porosity and permeability measurements) are usually more available.

The proposed method combines OHL and routine core analysis (RCA) to derive saturation functions for carbonate reservoirs with complex pore structure.

The proposed method uses a multi-regression technique to relate water saturation to height above FWL and rock quality index (RQI) for each reservoir rock type (RRT).

This method already been tested in carbonate reservoirs such as Shuaiba reservoir and Thamama-group formations.

This study used 58 core wells penetrating Thamama reservoir with permeability measurements covering six petrophysical groups. The comparison results show a good match between the calculated initial water saturation (Swi) from the dynamic model. The STOOIP calculations indicated good agreement (within 3% difference) between the dynamic and static models.

Keywords: Fluid Saturation, Reservoir Simulation, SCAL, Dynamic Model, Static Model.

INRODUCTION

Saturation functions are important and they dictate the initial fluid distribution in the reservoir. STOOIP calculation and future reserves are highly dependent on the initial oil saturation distribution at time zero. During geological time, oil migrates into geological traps and displaces the connate water which was filling the rock pore space (drainage process). The oil distributes itself within the pore space depends in many factors; height above free-water level (FWL), pore-through size, charging history, porosity, permeability and mineralogy. Unfortunately, in our reservoir models include only porosity and permeability as reservoir properties; the FWL can be calculated from depth. Other parameters are not included in the reservoir model. Historically, there are two main sources to generate saturation functions:

1 Laboratory measurements (SCAL) to establish drainage capillary pressure curve (Pc) per reservoir rock type from several plugs covering wide ranges of porosity and permeability.
2 Generate saturation function from open-hole logs (saturation-height function).

Both methods using deferent averaging methods to come up with single "average" Pc curve per RRT. These average curves used as input SCAL data in the dynamic models.

These average curves assume the water saturation is a function only of height above FWL. However, the log water saturation shows different Sw values at a given height per RRT as shown in Fig 1. That is why using a single Pc curve not be able to match initial Sw at different locations in the reservoir for a given RRT. Since a single Pc curve reflects the changes in Sw due to change in height only.

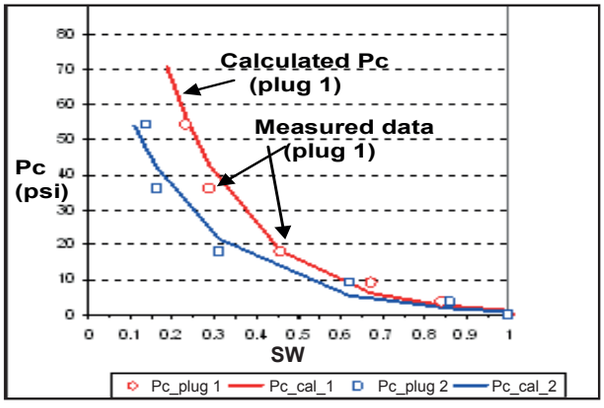

Fig. 1. Log water saturation versus height above FWL for RRT1

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METHOD

The proposed method relates the initial Sw distribution to height and other reservoir properties such as porosity and permeability.

The rock quality index (RQI) is defined using porosity and permeability as shown in equation 1.

$$RQI = 0.0314\sqrt{\frac{k}{\phi}} \quad (1)$$

Where: k = permeability in mD and ϕ = porosity (fraction).

Multi-regression technique was used to relate Swi to height (H) and RQI as shown in equation 2.

$$RQI(1 - Swi_{\log}) = a + bRQI + cLn(H) \quad (2)$$

Where: a, b and c are regression parameters, they are constants for a given RRT.

H = height above FWL in feet.

The log data was filtered by RRT and all Swi data which was affected by water injection was removed to ensure that all the regression data is at initial reservoir conductions. The multi-regression was performed using spread-sheet software. To evaluate the regression quality cross-plot of the left-hand side (LHS) of equation 2 versus the right-hand side (RHS) of equation 2 were plotted. R^2 was reported for quality check. Equation 2 can be solved for H as shown in equation 3.

$$H = Exp\left\{\frac{1}{c}\left[RQI(1 - Swi) - bRQI - a\right]\right\} \quad (3)$$

The height H above FWL can be converted to capillary pressure using equation 4.

$$P_c = 0.433 * H * (\rho_w - \rho_o) \quad (4)$$

Where: ρ_w = density of water and ρ_o = density of oil.

For a given reservoir rock type or petrophysical group, if the RQI is known, then Pc can be calculated at different ranges of water saturation.

Using simple statistical methods the mean RQI can be calculated for a given rock type or petrophysical group, then from equation 3 and 4 to calculate H and Pc using mean RQI.

SCAL data was used to validate this approach which will be shown in the validation section of this paper.

The capillary pressure also can be converted to J-function as shown in equation 5.

$$J(S_w) = \frac{0.2166}{\sigma \cos\theta}\sqrt{\frac{K}{\phi}}\ Pc \quad (5)$$

Where σ = oil-water interfacial tension (dyne/cm) and θ = oil-water contact angle.

Combining equation 1 and 5, an "average" J-function can be expressed in terms of mean RQI and Pc calculated using mean RQI as shown in equation 6.

$$\overline{J(S_w)} = \frac{6.898}{\sigma \cos\theta}\left|RQI\right|_{mean} * \left|Pc\right|_{mean} \quad (6)$$

The J-function in equation 6 is the average J-function for a given RRT or petrophysical group, since it is calculated using mean RQI and mean Pc. The average J-function was used as input saturation function in the simulator for a given RRT. This method requires only one average J-function for each RRT.

Calculation of Capillary Pressure: The simulator calculates the capillary pressure after the rescaling of the average J-function according to the porosity and permeability of each grid-cell. That is the reason; the average J-function was used as an input in the dynamic model instead of normal drainge Pc curve. The simulator would not rescale input Pc. For each RRT (SATNUM), the simulator will use the average J-function for this RRT, the will calculate Pc after rescaling as shown in equation 7.

$$P_c(S_w) = \frac{\sigma \cos\theta}{0.2166}\ \overline{JF} * \sqrt{\frac{\phi}{K}}\Bigg|_{grid-cell} \quad (7)$$

The Pc calculated from equation 7 is rescaled according to $\sqrt{\frac{\phi}{k}}$ of the grid cell in the dynamic model and thus change the value of Sw accordingly. So the calculated Sw is a function of height H and cell property (porosity and permeability). However, the Sw calculated from a single Pc curve is only a function of height.

Validation of the proposed Method: Validation of proposed method was done in two stages, first stage compare the results of the proposed method (calculated Pc) with SCAL data (brine-oil Pc data at reservoir conditions) for different plugs. The second stage involves comparisons of water saturation from log data versus dynamic model results.

Comparisons with SCAL Data: Even though matching laboratory SCAL data is not an objective of this work. However, SCAL comparison is used

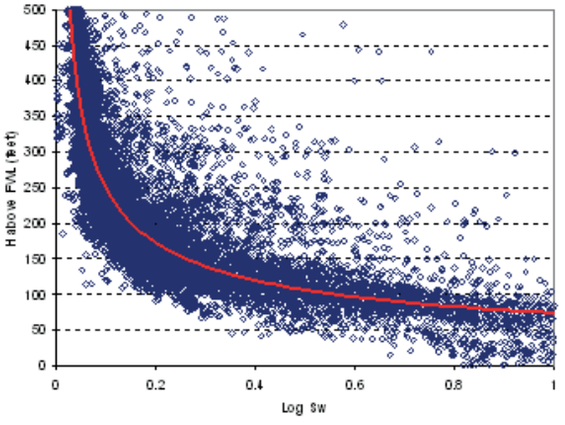

Fig. 2. Pc versus Swi comparing measured and calculated

as first stage validation of the proposed method. The calculated Pc was used to compare with oil/brine primary drainage Pc from porous-plate at reservoir conditions. For each plug sample RQI was calculated from porosity and permeability of core plug. The core samples used for comparison belong to one dominated RRT. Fig. 2 show the comparison results. The blue squares represent the laboratory measured data, the blue dotted line is the power fit of the laboratory data, the red circles represent the calculated Pc by the proposed method and the red curve is the power fit of the calculated data. All these figures indicated good agreement between the measured data and calculated values.

Comparisons with Open Hole Logs: Matching initial water saturation (Swi) from open-hole logs is our main objective of this work. Because the quality of this match has a major impact on STOOIP calculations and all the subsequent stages (history matching and predictions) coming after dynamic model initialization. All wells used for Swi comparisons should be screened to make sure all open-hole logs are reflecting Swi and not affected by injected water.

Initial water saturation match from Crest to Flank: Even though many early drilled wells are located in the crest area. However, it is important to select key wells covering the crest and flank reservoir regions, to ensure the Swi quality match. Flank wells usually are more challenging to match Swi from logs since they are drilled in the transition zone. The saturation functions should reflect the change in Swi from crest to flank before starting the history match stage. Figs. 3, 4 and 5 show initial water saturation

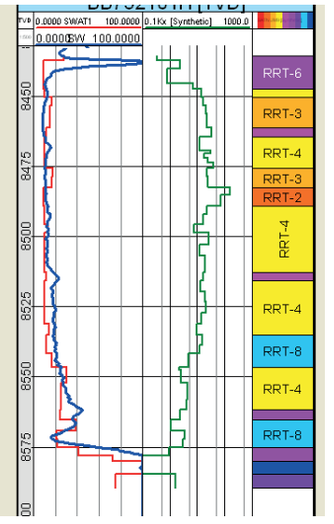

Fig. 3. Swi comparisons for crest well

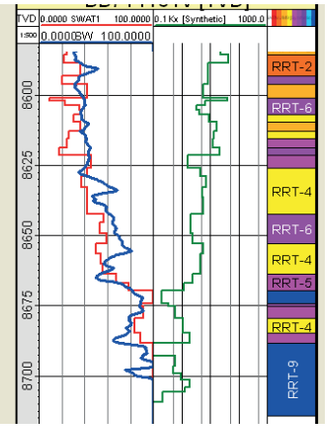

Fig. 4. Swi comparisons for mid-flank well

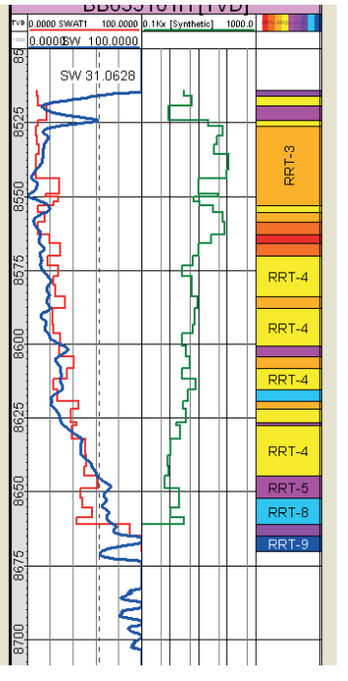

Fig. 5. Swi comparisons for flank well

match of three wells, the first well located in the crest area, the second located in mid-flank area and the third well is located in the flank area (transition zone). Fig. 3 show Swi comparison (first track) between log-Swi (blue curve) and model Swi (red curve), the second track shows permeability values (range from 0.1 to 1000 mD) and the third track shows reservoir rock type (RRT). Fig. 4 shows similar comparisons for the mid-flank well which also shows transition zone behaviour in the lower part of Swi log. Fig. 5 shows Swi comparisons for flank well.

***Limitations of the proposed method**:* The proposed method depends on permeability predictions in un-cored wells, if the model contains a good permeability predictions using neural-network for example, yield a better calculation of initial water saturations. Otherwise, the Swi calculations are not reliable. For such reservoirs where permeability data is limited or not available, a mitigation method could be used to replace the RQI variable in equation 2 with porosity and perform a similar regression. Then capillary pressure functions can be generated at different porosity ranges for a given reservoir rock type.

CONCLUSIONS

A robust method was developed to generate log-derived capillary pressure and J-functions and calculate the initial water saturation in a giant complex carbonate reservoir better than these industry standard methods. This method maybe utilized if a limited or no SCAL data is available. The limitation of the proposed method is its dependency on log-derived permeability data.

ACKNOWLEDGEMENT

The authors would like to acknowledge Abu Dhabi for Onshore Oil Operations (ADCO) for the permission and support to publish this work.

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