Quantification of Remaining Oil Saturation Using a New Wireline Dielectric Dispersion Measurement - A Case Study from Dukhan Field Arab Reservoirs

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Abstract

The accurate determination of remaining oil saturation (ROS) for Qatar Petroleum’s Dukhan oil field, under production since the 1940s, is a key requirement for an ongoing revision of the field development plan. In 2009 several dedicated observation wells were drilled and cored. Extensive wireline data acquisition of nuclear, resistivity, acoustic, and nuclear magnetic resonance (NMR) data was performed with the objective to quantify the remaining oil saturation from log measurements and compare these log-based results with remaining oil saturations from core analysis.

The Dukhan field is under water flooding for secondary recovery, and changing water salinities resulting from the mixing of salty formation and fresh injection water make any resistivity-based calculation of remaining oil saturation a difficult task. Faced with these challenges Qatar Petroleum chose to field-test a new wireline dielectric dispersion tool to obtain resistivity independent remaining oil saturation information. A second objective was to test the estimation of Archie’s cementation factor $m$ from dielectric dispersion measurements, as Qatar Petroleum had evidence that $m$ varies vertically and laterally across the reservoir.

Remaining oil saturations obtained from the dielectric dispersion tool are presented and compared with resistivity-based values, NMR diffusion-relaxation analysis results, and core-derived Dean-Stark oil saturation measurements. The results confirm the ability of the dielectric dispersion tool to give a reliable measurement of remaining oil in place. Estimation of Archie’s cementation factor $m$ appears to confirm expected variations especially in the Arab-C reservoir in certain parts of the field, with the dielectric dispersion based remaining oil saturation agreeing with the observed fluid production.

Introduction

Dukhan is a large mature field located onshore Qatar, approximately 80 km west of Doha. The field which was discovered in 1941 forms a north-south plunging anticline approximately 70 km long by 8 km wide and has more than 750 wells penetrating the main producing reservoirs. The Upper Jurassic (Kimmeridgian) Arab-C and Arab-D are the main reservoirs in terms of size and production potential. The Middle Jurassic Uwainat contains smaller amounts of oil and gas, whereas non-associated gas is present in the Permo-Triassic Khuff reservoir.

The Dukhan field is divided into four inter-connected sectors that extend from North to South: Khatiyah, Fahahil, Jaleha and Diyab (Fig. 1). The division into sectors does not reflect subsurface segmentation of reservoirs. Rather, it is based on allocation of wells to surface facilities.
The two northern sectors Khatiyah and Fahahil contain saturated oil with a large gas cap. The third sector, Jaleha, also contains saturated oil while the southernmost sector, Diyab, is under saturated (Barrios Vera et al. 2009).

Arab-C and Arab-D rocks consist of limestone and dolomite, with high-permeability grainstone layers, particularly in the upper sections (Fig. 2). Diagenesis played a minor role in modifying the reservoirs properties and hence most of the primary interparticle porosity is preserved in the grainstone intervals (Fig. 3). However, dolomitization has affected the rock quality by creating moldic and intercrystalline pores. The different reservoir zones are separated and overlain by anhydrite layers.

The development of the field commenced in 1949, with the drilling of the first wells in the northern sectors of Khatiyah and Fahahil and historical production included natural depletion from 1949 to 1970, gravity (“dump”) water flooding from 1970 to 1990, and power water injection from 1990 onward.

![Fig. 2: Diagram displaying Arab-D profile and environment of deposition (After Trabelsi et al. 2009).](image1)

![Fig. 3: Photomicrographs displaying highly porous and permeable lime peloidal skeleton grainstone.](image2)

Dukhan field is currently undergoing a revision of the field development plan, and a critical input to this study is reliable information on remaining oil saturation (ROS). Changing water salinities resulting from the mixing of high-salinity formation and fresh injection water make any calculation of ROS a difficult task. This applies to traditional openhole resistivity based methods, as well as for pulsed-neutron capture (sigma) saturation determination in cased wellbores.

Faced with these challenges Qatar Petroleum chose to field-test a new wireline dielectric dispersion tool to obtain resistivity independent ROS information. A second objective was to test the estimation of the tools textural answers in carbonates (Archie parameters $m$ and $n$) from dielectric dispersion measurements, as Qatar Petroleum had evidence that Archie’s parameters $m$ varies vertically and laterally across the reservoir. Archie’s saturation exponent $n$ is also expected to change going from drainage to imbibition stage during the water-flooding (Ma et al. 2005).
This paper compares the quantification of ROS from the dielectric dispersion measurement with that of other logs and core based Dean Stark oil saturation.

Remaining Oil Saturation
ROS is defined as the minimum oil saturation that is actually achieved on a microscopic basis (i.e., within those pores contacted and swept by the displacement process). This value is different from the “true” residual oil saturation (SORw) obtained from displacement experiments (Barrios Vera et al. 2009). Many methods have been developed to determine ROS in the field. Chang et al. (1988) and Causin et al. (1990) provide discussion and comparison between the various methods.

Logging Program
In 2009 several dedicated observation wells were drilled and cored with the objective of acquiring additional data for an ongoing field study, in particular information on ROS. These observation wells have been positioned to penetrate partially swept areas of the field. A field-test of a new wireline dielectric dispersion tool was conducted in three of the observation wells (two in the Jaleha sector and one in the Diyab sector).

Extensive wireline data acquisition of nuclear, resistivity (both laterolog and induction), acoustic, nuclear magnetic resonance (NMR), borehole electrical image and formation testing data was performed with the objective to quantify ROS from log measurements and compare these log-based results with ROS from core analysis. NMR data is also used for permeability analysis and integrated with borehole image data for rock characterization.

Water sampling with the formation tester tool in each of the three field-test wells provided critical values of formation water salinity as input into the resistivity based saturation analysis. A new downhole pH measurement was used to determine the optimal timing to start the sampling process, and focused sampling was used to get the best possible sample quality at reduced sampling times (Xian et al. 2007; Del Campo et al. 2006).

Coring Program
In Dukhan, low invasion coring was selected as the preferred method for estimating ROS. Therefore a data collection program of low invasion cores using bland water-based mud and deuterium oxide as tracer was conducted in partially swept zones of the reservoir.

In all wells coring achieved 100% core recovery and efficiency. Cores were photographed on site under UV light to detect hydrocarbon fluorescence and aid in plug selection (Fig. 4). Vertical plugs were immediately cut from these cores at the rig site using liquid nitrogen as a cooling fluid for plugging. The plugs were then preserved using coreseal and following a proper and carefully planned preservation method. The preserved state plugs were then used for measuring ROS, residual oil saturation, electrical properties, wettability, capillary pressure and relative permeability (SCAL) data.

Dean Stark testing was conducted on all remaining oil-saturated plugs following a detailed specific method. Current water saturation was corrected for mud filtrate invasion. The correction was made by accounting for the tracer concentration in the drilling mud and in the extracted pore water of the sample.

At the time of writing of this paper the final results were not available, but preliminary data reports a high variability of current water saturation (i.e., ROS) from plugs representing the Arab-D reservoir. Current water saturation in well C (Diyab sector) ranges from about 17% to 94% with an average of 56% (ROS between 6% and 83% with an average of 44%) and in well B (Jaleha sector) ranges from about 10% to 92% with an average of 57% (ROS between 8% and 90% with an average of 43%). These preliminary results will undergo a further quality control process and then be compared and integrated with the current water saturations determined from the various log measurements.
Dielectric Dispersion Measurement

A new wireline dielectric dispersion measurement introduced in 2008 is aiming at overcoming the measurement limitations of previously existing technology to provide extra information for more accurate petrophysical formation evaluation (Hizem et al. 2008).

Three main physical phenomena contribute to dielectric wave propagation: displacement of the electronic cloud of atoms, orientation of electric dipoles, and polarization effects at grain-to-grain interfaces (Fig. 5). At high frequencies electronic polarization and molecular orientation can be related to rock matrix and fluid permittivity, with the relative permittivity of common minerals ranging from ~4.6 for sandstone to ~9 for limestone, and ~2 for oil. Water molecules, which are strong electric dipoles, have a much larger relative permittivity of ~50 to 80, depending on salinity and temperature. Hence a high-frequency dielectric measurement provides an excellent measure of water-filled porosity. Interfacial polarizations provide information on the rock texture at lower frequencies.

The dielectric dispersion tool is pad-mounted with two transmitters and eight symmetrically located receivers (Fig. 6) working in longitudinal and transversal mode. It acquires radial information of conductivity and dielectric permittivity up to 4 in. into the formation. Two additional probes measure mud and mudcake properties to provide input for the data interpretation.

One of the new features is the continuous measurement of dielectric dispersion (the change of dielectric properties with frequency). For this the tool measures dielectric properties at four frequencies between 20MHz and 1GHz, providing a measurement of the dielectric dispersion at a 1-in. vertical resolution.

The data processing and interpretation workflow consists of three main steps. The tool processing converts the raw measurements (attenuation and phase shift for each spacing, frequency and polarization) into apparent permittivity and conductivity for each spacing and frequency, and the associated uncertainty of each channel. A radial inversion is then performed using all measurements, each weighted with its uncertainty. The outputs are conductivity and permittivity of each layer at each frequency. Two models are available in this step, a mudcake model which solves for mudcake and one radial zone, and a radial model for a shallow invasion profile with a shallow and a deep radial zone.

A petrophysical model transforms these results into petrophysical parameters for each layer. Acquisition uncertainties are included in the inversion and propagated to provide uncertainties on the final results. The main answers of this step are water-filled porosity, water salinity, an equivalent flushed-zone resistivity ($R_{xo}$) computed from the dispersive conductivity measurements and a textural parameter from the dielectric dispersion analysis. In carbonates this textural parameter is equivalent to the Archie parameters $m$ and $n$, with the assumption of $m=n$. Water-filled porosity is compared with a total porosity measurement to compute the dielectric flushed-zone saturation ($S_{xo}$) independent of resistivity.

Dukhan Examples

In the following sections we discuss in several examples the results of the dielectric dispersion tool field-test in Dukhan. ROS obtained from the dielectric dispersion tool is presented and compared with resistivity-based values, NMR diffusion-relaxation station ($D-T_1$) measurements, and ROS from Dean-Stark analysis of core plugs for three key wells (called well A, well B, and well C).
Resistivity-based saturations were computed using Qatar Petroleum’s standard petrophysical model with Archie parameters $m$ and $n$ taken equal to 2. Water resistivity ($R_w$) values were taken from samples of formation water in each of the wells. $R_w$ in the different wells and reservoirs varies between 195,000ppm to 45,000ppm NaCl equivalent, highlighting a variable mix of original formation water (220,000ppm NaCl equivalent; Wan Hasan et al. 2009) and injection water. Thus a priori knowledge of the formation water salinity is a key to obtain reliable saturation estimates from a resistivity measurement.

NMR $D-T_1$ station measurements provided additional resistivity independent flushed zone saturation answers (Cao Minh et al. 2003). Station data were analyzed using the newest computation method correcting for restricted diffusion effects and formation water salinity (Zielinski et al. 2010).

Estimation of the textural information from dielectric dispersion appears to confirm expected variations of the Archie parameters especially in the Arab-C reservoir in certain parts of the field, with the dielectric dispersion based ROS values agreeing with observed fluid production.

Unfortunately no special core analysis is available to validate the apparent variations in the textural properties as highlighted by the dielectric dispersion tool.

In the following discussion composite displays for the three example wells are shown in the following format:

- **Track 1**: Dielectric dispersion tool estimated invaded zone water salinity
- **Track 2**: Gamma ray, caliper, matrix permittivity, and textural information from dielectric dispersion
- **Track 3**: Saturations from dielectric dispersion, resistivity ($m=n=2$), NMR $D-T_1$ stations and core, with shading representing ROS from dielectric dispersion.
- **Track 4**: Lithology
- **Track 5**: Depth
- **Track 6**: Resistivity: array laterolog curves 3 and 5, array induction 60in and 90in curves, shallow resistivity, and dielectric dispersion tool computed $R_{ko}$
- **Track 7**: Porosity: total porosity, NMR porosity, dielectric dispersion water-filled porosity, NMR $D-T_1$ station porosity and water volume, and core porosity
- **Track 8**: NMR porosities and porosity partitioning into small pore, capillary bound, and free fluid porosity
- **Track 9**: NMR $T_2$ distribution and $T_2$ logarithmic mean
- **Track 10**: Dielectric dispersion tool computed permittivity and conductivity for the four frequencies

**Well A**

Well A, located in the Diyab sector, was the first well logged during the field-test. Logging covered both the Arab-C and Arab-D reservoirs; however, core was taken only in the Arab-D. The drilling mud salinity in this well was relatively high; therefore the formation water salinity input to the dielectric processing was constrained to a range close to the mud filtrate salinity to ensure stability of the inversion. Constraining the water salinity does not affect the accuracy of the inverted water-filled porosity.

In the Arab-C interval (Fig. 7) the dielectric dispersion data show the reservoir as water-bearing, which agrees with observations in this sector of the field. The dielectric dispersion tool computed shallow-zone resistivity (dark blue curve in track 6) matches well with the measured shallow zone resistivity (light green curve in track 6).

The traditional resistivity-based analysis using $m=n=2$, however, shows saturations (dashed dark blue curve in track 3 of Fig. 7) up to 30% to 40%. The textural information from dielectric dispersion (light blue curve in track 2 of Fig. 7) shows quite high values, in the range of ~2.5 and above, suggesting that the Archie parameters used in the traditional resistivity analysis may not be correct. Substituting $m$ and $n$ in Archie’s formula with the textural information from dielectric dispersion gives saturation from resistivity.

**Fig. 7**: Well A composite display for the Arab-C reservoir. The blue star in the depth track indicates the location of the formation water sample.
analysis that is more in line with the other data and field observations (Fig. 8). A formation water sample taken at the base of the Arab-C reservoir (blue star in depth track of Fig. 7) further confirms the reservoir being water-bearing.

![Fig. 8: Well A comparison of resistivity-based water saturation $Sw$ using $m=n=2$ (dark blue curve in left side saturation track) and resistivity-based saturation using the textural information from dielectric dispersion (light blue curve in right side saturation track) for the Arab-C reservoir.](image)

**Well B**

Well B was drilled in the Jaleha sector, and both Arab-C and Arab-D reservoirs were cored. The mud filtrate salinity in this well was lower compared with well A and consequently no constraint was used in the dielectric dispersion data processing. The computed flushed zone water salinity (black curve in track 1 of Figs. 9 and 10) is, with only a few variations, close to the mud filtrate salinity suggesting that the invaded zone was completely flushed of formation water within the depth of investigation of the measurement.

The ROS values in the Arab-C reservoir (Fig. 9) are in the range of 20% to 30% and in excellent agreement with results from core analysis and NMR diffusion-relaxation stations. Resistivity based analysis using $m=n=2$ generally shows higher saturations. Similar to well A, the textural information from dielectric dispersion shows higher values between 2 to 2.5, and locally even higher. Using these textural values in the resistivity analysis will give saturations closer to the results computed from the other log and core measurements.

![Fig. 9: Well B composite display for the Arab-C reservoir. The blue star in the depth track indicates the location of the formation water sample.](image)

The results for the Arab-D interval (Fig. 10) show an excellent agreement of ROS from the dielectric dispersion tool, resistivity based analysis, NMR relaxation-diffusion stations, and core analysis. ROS in the flushed zone of the reservoir (x950-x845 ft) is between 15% and 30%, and reaches 40% to 50% at the top above the current oil-water contact (x845 ft).

As already observed in well A, ROS appears to vary with rock quality. Better porosity and permeability layers such as at depths x855-x845 ft, x880-x862 ft, and x940-x920 ft, show lower ROS values in the range of 15% to 20%. ROS in zones of lower rock quality generally is in the range of 20% to 30%.

The dolomitic zone in the lower Arab-D (x980-x950 ft) shows a discrepancy between the results from the dielectric dispersion tool and other data, with core and resistivity results suggesting a higher ROS. Textural information from dielectric dispersion in this interval shows higher values in the range of 2.5, sometimes even higher. Using this information in the resistivity analysis gives saturations closer to that of the dielectric dispersion tool. In limestone intervals of the Arab-D textural information from dielectric dispersion is in the range of 1.9 to 2.2.
Fig. 10 (left): Well B composite display for the Arab-D reservoir. The red star in the depth track indicates the location of the NMR $D-T_1$ station of Fig. 12.

Fig. 11 shows an example of the NMR $D-T_1$ station analysis for the depth of x880 ft (red star in depth track of Fig. 10). The position of the main signal in the upper right of the graph highlights the difficulty with this analysis in the Dukhan reservoir. The diffusion coefficient and NMR $T_1$ signal of the light Dukhan oil are very similar to those of the formation water, and both signals appear close or overlapping. The viscosity of the reservoir oil is quite low, similar to the viscosity of water at reservoir conditions, and likely results in deep invasion of the mud filtrate. Despite this complexity the results in terms of oil saturation match well with the depth log analysis.

Fig. 11: Well B NMR relaxation-diffusion station analysis at depth x880 ft (red star on Fig. 10). The upper left graph shows the diffusion-$T_1$ relaxation plot, the lower left graph the computed oil and water $T_1$ distributions. In the lower right the computed results are displayed ($\Phi_i =$ total porosity, $\Phi_{iw} =$ water-filled porosity, $\Phi_{io} =$ oil-filled porosity, $\Phi_{ig} =$ gas-filled porosity, $\text{Vis} =$ oil viscosity from oil $T_1$ logarithmic mean).

Well C

Well C was also drilled in the Jaleha sector. Both Arab-C and Arab-D reservoirs were cored. Drilling fluid salinity was the lowest of all the three example wells with filtrate salinity of ~20,000 ppm NaCl equivalent. The computed flushed zone water salinity (black curve in track 1 of Fig. 12) is very similar to the mud filtrate salinity, again suggesting that most of the invaded zone was completely flushed of formation water.

Results for the Arab-C reservoir (Fig. 12) show a similar picture to well B, and ROS values from the dielectric dispersion tool are in the range of 20% to 30%. Core results agree well with this information, however, resistivity-based
analysis indicates higher oil saturation. Similar to wells A and B the textural information from dielectric dispersion shows higher values than \( m=n=2 \), which was used in the resistivity analysis. NMR relaxation-diffusion analysis also indicates higher saturations for the Arab-C reservoir.

The upper Arab-C in this well is of low quality rock with poorly developed porosity. Pore fluid is mainly bound water, as shown by the NMR tool, and only a small amount of oil.

The results for the Arab-D reservoir are very consistent with the results of well B. Remaining oil saturation from the dielectric dispersion tool, resistivity based analysis, NMR relaxation-diffusion stations and core data are again in excellent agreement, with ROS in the range of 15% to 30%. The better quality zones show ROS generally lower with values of 10% to 20%, and in the lower quality zones (i.e. lower porosity upper Arab-D) ROS is in the range of 20% to 30%.

The dolomitic zones in the lower Arab-D in this well, similar to well B, show larger variations in ROS from the different log and core measurements. Core and dielectric dispersion data show a better agreement with resistivity-based analysis, which is most likely in error owing to higher \( m \) and \( n \) values in this lithology as suggested by the textural measurement from dielectric dispersion. In limestone intervals of the Arab-D textural information from dielectric dispersion is in the range of 1.9 to 2.2, which is also shown in the good agreement of dielectric dispersion- and resistivity-based ROS.

**Fig. 12 (left):** Well C composite display for the Arab-C reservoir. The blue stars in the depth track indicate the location of the formation water samples.

**Conclusions**

Three field-tests of a new wireline dielectric dispersion tool were conducted in the Dukhan field Arab reservoirs with the objective of evaluating the tool’s ability to provide a reliable measurement of ROS in carbonates and to acquire a resistivity independent measurement of ROS.

Good quality data were obtained in different borehole fluid salinities, and the computed ROS values from the dielectric dispersion measurement are in excellent agreement with resistivity-based, NMR \( D-T_1 \), and core-derived Dean-Stark analysis. Exact knowledge of the formation water resistivity \( R_w \) is however critical for an accurate resistivity analysis.

In general ROS in the Arab-C reservoir is higher than in the Arab-D reservoir, which is also reflected in the textural computation from dielectric dispersion. For the Arab-D reservoir the textural information in limestone intervals varies from 1.8 to 2.1, close to the value of \( m=n=2 \) used in the traditional resistivity-based analysis. Resistivity-based results and dielectric dispersion results are therefore close. Dolomitic intervals in the Arab-D show generally higher values from the dielectric dispersion textural analysis.

In the Arab-C reservoir the textural computation from dielectric dispersion is more variable, and generally also reaches values of ~2.3 to 2.5, and in few cases even higher. Saturations computed with \( m=n=2 \) therefore show higher ROS values compared with the dielectric dispersion results. This may not be correct, as suggested by the Arab-C results of well A, where resistivity-based analysis does not agree with the field observations, and where a clean sample of formation water was obtained at the bottom of Arab-C. The dielectric dispersion tool in this interval appears to provide the correct answer.

Log-based values of ROS appear to vary with rock quality, with the better quality intervals showing lower ROS. This has also been observed in the core analysis, and is the subject of a separate study.

The field-test results from the three wells, together with the other log and core measurements, provided Qatar Petroleum with a rich dataset for an integrated analysis of ROS in Dukhan.
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References


