

A New Integrated Technique for Saturation Height Function Modeling based on Modified EQR Method

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Abstract

Equivalent Radius (EQR) is a relatively new normalized capillary pressure method for modeling of the saturation height function. In this method petrophysical data such as well logs, special and routine core analysis have been used in an integrated manner.

The main purpose of this study is to investigate dynamic behavior of the fluid flow through porous media with a new integrated technique for saturation height function modeling. Amongst different methods, EQR method that originally developed by Engstrom in 1996 has been selected for further study. Although this method can model the initial water saturation with high accuracy but it only can be applicable for low permeability formations. However, there is still an incomplete understanding its application for other rock units with higher degree of porosity and permeability. For this purpose, we present a Modified EQR (MEQR) based on iterative curve fitting procedure. To demonstrate the capabilities of MEQR method, one of the Iranian oil field data located in southwest of Iran with quite high degree of permeability in its porous sandstone layers has been used.

It is shown that this technique can accurately predict the initial water saturation in all rock types and in each cell of the reservoir with very good correlation coefficient achieved in comparison with interpreted saturation well logs.

Keywords: Saturation Height Function, Equivalent Radius (EQR), normalized capillary pressure, dynamic behavior

Introduction

Saturation height function modeling allows spatial distribution of S_w , normally use for volumetric calculations of hydrocarbons in place in a dynamics simulation process of the reservoir. There are some well-known practical methods for producing field wide saturation-height function that generally relates capillary pressure curves to porosity, permeability or various rock types of the reservoir. We can mentioned here some classical and still in use methods such as Leverett's J-function approach (Leverett, 1941), Johnson in 1987, Cuddy et al. in 1993 and Skelt and Harrison in 1995. But Engstrom et al. 2005 have revealed that none of the Saturation height function modeling procedures precisely enough could reflect the capillary pressure properties low permeability formation and also could not represent the transition zone created above FWL.

They show that the EQR is a water saturation modeling technique based on normalization of capillary pressure data resulted from core analysis in the laboratory by capillary entry pressure (P_{ce}). Irreducible water saturation (S_{wir}), the capillary entry pressure (P_{ce}) and the capillary shape function (CSF) are three main fitting parameters to normalized capillary pressure curves or EQR curves. In this study, we use curve fitting method to find best matching curve of EQR versus as normalized non-wetting saturation phase divided by Irreducible water saturation. This new modification on EQR has made it applicable not only for low permeability formation but also it is useful to exactly determination of water saturation in high porosity rock types.

The main difference between our study and similar previous works is in using conversion coefficient. Conversion coefficient is a parameter that is identified in rock and fluid interaction study for Lab to reservoir condition conversion.

The weak point of other methods is that the conversion data for reservoir condition may alter the intrinsic nature of data. We insist to develop a method to do this conversion without any data manipulation. In the following sections we describe the geological descriptions of the case study where we gather required data for modeling and then we briefly review the theory of EQR. Finally, we will prove that the obtained results of saturation modeling have exactly correlated with $S_w(\log)$ and also compatible for all existed rock types of the reservoir.

Geological setting and available required data

The Under study oil field is discovered by NIOC in 2002 and is located in the southwest of Iran, generally is composed of shale and sandstone sequences. The main reservoir formation (Sarvak) of this field is made of porous sandstone is generally of good to very good quality. The Sarvak reservoir has porosities that typically vary between 0.21 and 0.41 and air permeabilities of 0.4 mDarcy and 20 mDarcy is conducting fluid flow through water drive component beneath of the reservoir. This reservoir has located in depth of 3110 TVDSS and overlaid by a thick shaly and marly seal cap rock.

Among all 64 drilled wells in the Under study field, routine and special core analysis data are only available in three wells of 4, 16 and 23 including core porosity, absolute/relative permeabilities, capillary pressures, wettability and pore size distribution tests. Based on typical values of surface tension and contact angle oil-water system measured in core laboratory, all mercury injection and oil-water Pc curves have converted into real reservoir conditions. In the laboratory, wettability is characterized using different methods, among them Amott method is used more since its results are more reliable. According to this method, wettability is expressed as “mixed-wet sandstone.

Indeed, before saturation modeling it is imperative to realize in a single reservoir layer maybe there are some dissimilar rock units that hydraulically show different behavior in the real condition. For instance, it is clear that high quality of rock types with high degree of porosity and permeability have minimum capillary pressure rather than poor quality of rocks. In this circumstance, using of SCAL results related to all rock types in the same manner can leads to miscalculation of transition zone above FWL and final predicted water saturation. To overcome this shortcoming, we simply categorized SCAL data typically based on porosity and interpreted water saturation well logs of the cored wells. Table 1 has reported all SCAL porosity and permeabilities in two different classes. In class I, good quality of rock samples with porosity higher than 0.24 and permeability of higher 8 mD has classified. Whereas, the second group of rock samples with porosity and permeability less than the first group has arranged in class II.

Table (1):-Routine core analysis information of three cored wells.

Sarvak	Sample	Well	porosity	Permeability (MD)
Class I	S.1	Well-4	0.25	12.5
	S.2	Well-4	0.26	11.6
	S.3	Well-4	0.29	8.6
	S.4	Well-4	0.26	7.9
	S.5	Well-4	0.24	10
	P.1	Well-16	0.25	12
	P.2	Well-16	0.27	13
	P.3	Well-16	0.31	16
	P.4	Well-16	0.28	8.56
	H.1	Well-23	0.33	11.4
	H.2	Well-23	0.41	20
	H.3	Well-23	0.25	6.38
	Class II	S.6	Well-4	0.14
S.7		Well-4	0.13	3.84
P.5		Well-16	0.18	6.12
P.6		Well-16	0.11	2.66

Petrophysical rock typing

Similarly when the logs of three cored wells have evaluated, we found out that the variations in porosity and saturation well logs from top of Sarvak to a given depth are constant in all 3 wells and then after this special point we observed the amount of porosity decreases and the amount of water saturation increases up to bottom of the formation. Figure 1 shows the variations trend of porosity and Sw logs in wells of 4, 16 and 23. As illustrated in this figure, there is a good quality of rocks underlaid by a poor quality formation. The rock samples with high degree of porosity and permeability (class I) are on good quality rock type and the rock samples with low degree of porosity and permeability (class II) are on poor quality rock type. The location of available MICP samples (red points) through well section in each cored wells have been illustrated.

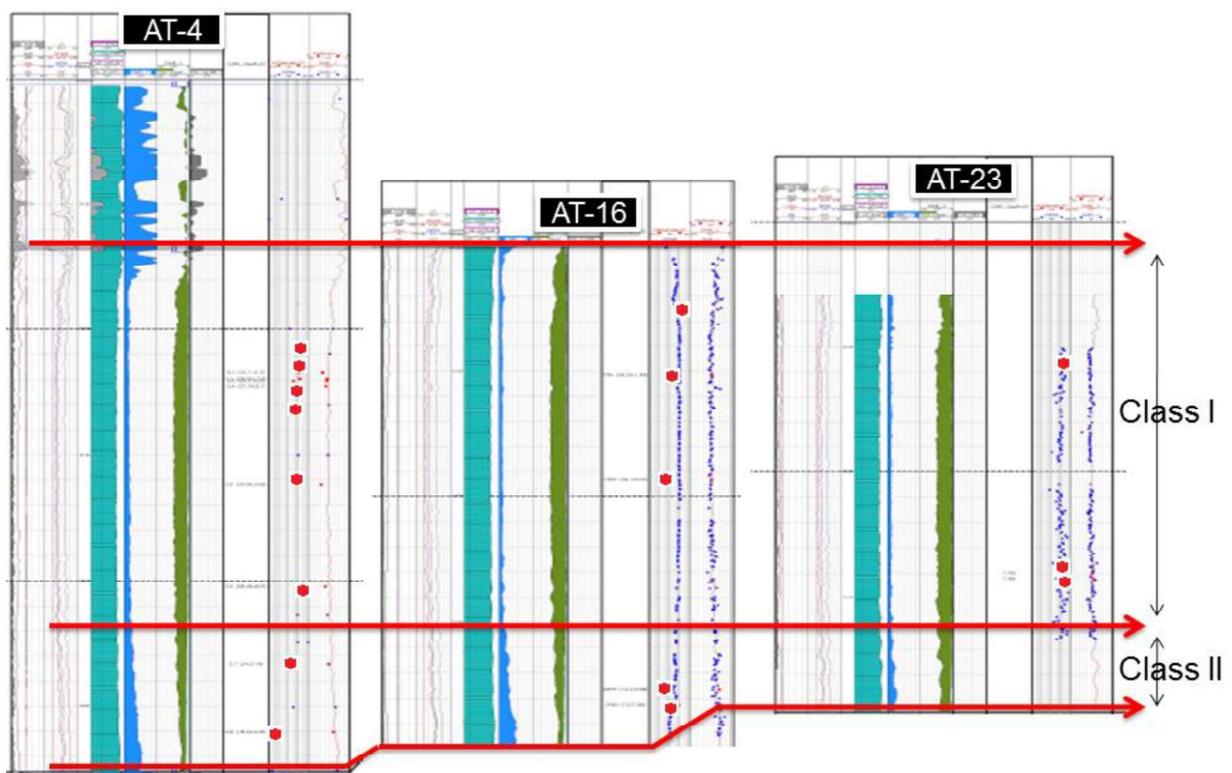


Fig.(1)Petrophysical rock typing of Sarvak formation based on porosity and saturation well logs.

According to above rock petrophysical rock typing, we have used normalized mercury injection capillary pressure (MICP) curves to define related entry capillary pressures for each MICP curve. In order to grouping of rock samples, only mercury-air capillary pressure have been used and rather than centrifuge samples due to having high transition zone and more representative entry pressures.

Similarly, we observed the same results with above rock classification. Figure 2 demonstrated the grouping of MICP samples into two different classes with considerable difference between two values of P_{ce} . Distinct dynamic behavior of good quality rock type (class 1) with low entry pressure obviously is distinguishable from poor rock type with higher entry pressure.

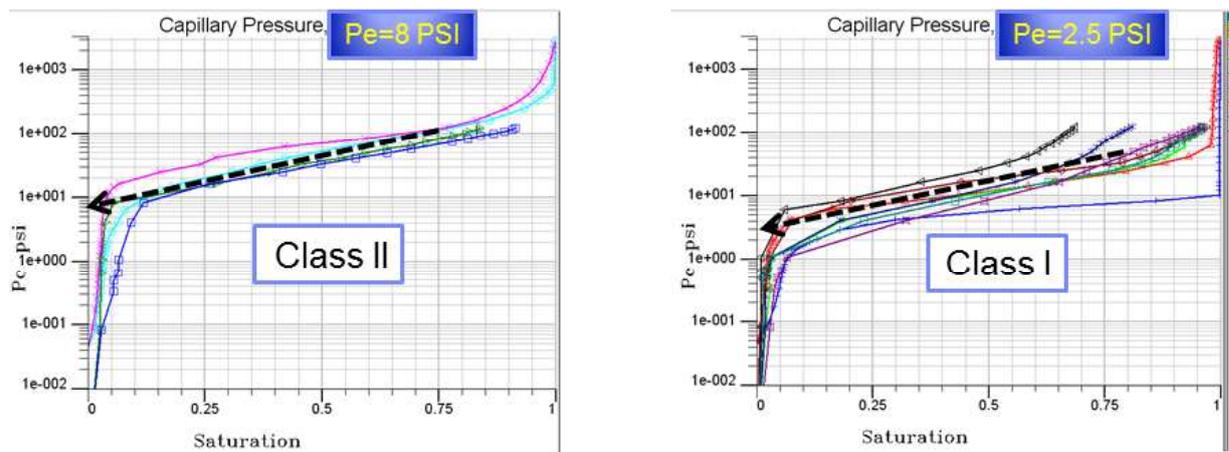


Fig.(2) MICP curve results in two different class of rock

Equivalent Radius approach

EOR method as mention in last section basically has extended in low-permeability chalk reservoirs with high capillary pressures and large oil/water transition zones. Some investigators like Nils et al, Bech et al., in 1999 and Jensenius and Ameradahave, 2003 have modified this procedure and reported water saturation height function can exactly determined the initial water saturation distribution in the reservoir. In this paper, we will acclaim the EQR can be applicable for all reservoir rock types even high porous and permeable formations. In this method, Irreducible water saturation and capillary pressure are functions of porosity so that with gradually decreasing of porosity, both of them would be increased Engström, 1995

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whereas, the majority of conventional methods suppose these parameters to be invariant (Nile et al, 1999).

Equivalent Radius model, the irreducible water saturation, Sw_{ir} , and the capillary entry pressure, P_{ce} , as input variables to an averaging procedure have been used. The normalized capillary pressure (so-called EQR), and the normalized non-wetting phase saturation, (Snw') can be computed as follows:

$$EQR = MIP_{ce}/MIP_c \text{ and } Snw' = (1 - Sw)/(1 - Sw_{ir})$$

Where P_c is the capillary pressure and Sw is the water saturation.

Capillary shape functions (CSF) have explicitly produced by plotting normalized MICP data through an iterative curve fitting procedure against Snw' for individual SCAL data. On the other word, the normalized non-wetting phase saturation can be described as function of EQR.

$$Snw' = F(EQR)$$

F in the above equation is a non-linear function depends on the nature of MICP curve and implicitly represents the interconnections and distribution of pore throats. Therefore, it is very important to exactly define CSF with high degree of compatibility to real model prediction.

For this purpose, P_{ce} , Sw_{ir} and CSF values have consecutively calibrated for a given sample. In other words, an iterative process using the powerful curve fitting method has applied so that all basically three parameters adjusted to the model prediction.

For this issue, we provide a powerful curve fitting and statistical analysis in an encoded Matlab program. In this program, there are extensive range of predefined linear and nonlinear mathematical models for applying to data set. Then we can select the best model based on descriptions of the models and preview of the fit. In the next step, the selected model change automatically parameter values, knocking out data points, adding weighting and error bar values until the best model parameters have been observed. It should be highlighted that adjustment or calibration of parameters must be done how there is only a unique representative equation with fixed framework and variable constants for all samples as following:

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$$S_{nw}' = (A + (B / (1 + \exp(((((-1) * C) + (D * \ln(EQR))) + (E * EQR))))))$$

In the above relation CSF is a complex non-linear function included five independent constant. Table 2 reported these constants of EQR equation for all core samples and the calibrated values of entry capillary pressure and irreducible water saturation.

Table (2): PeCalib, SwirCalib and constants of EQR equation for all core samples in two different rock types

Rock type	Sampl e	A	B	C	D	E	PeCali b.	SwirCali b.
Class I	S.1	1.52884	-	6.14090	-	1.38522	0.8	0.06
		2	1.47437	1	2.67993	7		
	S.2	0.03982	1.48291	0.45837	0.22337	3.62458	2	0.11
		2	2	9	2	4		
	S.3	0.05948	1.67474	-	0.82309	1.48762	6.3	0.17
		2	8	2.29254	9	2		
	S.4	-	1.18122	-	2.05044	-	10	0.17
		0.01195	8	4.02949	9	1.12443		
	S.5	-	1.10774	-	1.70955	-	1.7	0.12
		0.00063	6	-3.2552	3	0.53588		
	P.1	0.84636	-	1.15200	2.62145	3.1	0.15	
		0.01051	7	1.45692	2			7
P.2	0.03303	1.10110	-	0.47441	2.1	0.15		
	1	4	-0.3171	9			3.32115	
P.3	0.02545	-	2.10597	-	3	0.12		
	5	1.0772	3.82751	9			0.48076	

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	P.4	0.00327	1.10794	-	1.23330	0.41387		
		3	3	2.16151	4	5	1.7	0.1
	H.1	0.05948	1.10774	-	-	-		
		2	6	2.22254	2.63593	1.12443	1.5	0.15
	H.2	0.06489	1.02587	-	1.63256	4.02563		
	8	3	1.52125	8	2	1.6	0.14	
			1.69853	-	1.12554	2.65326		
	H.3	0.02516	2	1.25487	8	6	2.8	0.14
	AVG	0.15311	0.99475	-	0.60120	1.35560		
		5	2	1.31164	2	9		
Class II	S.6	0.04799	2.80229	-	0.20970			
		9	6	1.60727	7	4.20365	0.8	0.1
	S.7	0.02860	2.50946	-	0.32913	3.25145		
		7	8	1.25793	5	1	6	0.17
	P.5	0.10188	2.92149	-	0.32259	3.29806		
		6	7	1.39747	6	3	6.5	0.15
	P.6	0.36581	3.05698	-	0.36325	3.54784		
		3	8	1.45852	6	5	4.1	0.16
	AVG	0.13607	2.82256	-1.4303	0.30617	3.57525		
		6	2		3	2		

Now, we can provide the initial water saturation equations as EQR model for two existed rock types of Sarvak formation as follow:

Class I	$S_{nw}' = \frac{0.1531 + (0.994 / (1 + \exp(-1)^{-1.311 + (0.6012 \cdot \ln(EQR)) + (1.355 \cdot EQR))))}{(0.136 + (2.822 / (1 + \exp(-1)^{-1.43 + (0.306 \cdot \ln(EQR)) + (3.575 \cdot EQR))))}$
Class II	$S_{nw}' = \frac{0.1531 + (0.994 / (1 + \exp(-1)^{-1.311 + (0.6012 \cdot \ln(EQR)) + (1.355 \cdot EQR))))}{(0.136 + (2.822 / (1 + \exp(-1)^{-1.43 + (0.306 \cdot \ln(EQR)) + (3.575 \cdot EQR))))}$

It should be noted that, before saturation modeling all SCAL data have converted to real reservoir condition. This is based on laboratory fluid contact angle and interfacial tension forces of real reservoir fluids.

In previous jobs, for matching initial water saturation with water saturation logs, the conversion factors were continuously manipulated. We believe that, this method is not acceptable because we are not allowed to alter the intrinsic nature of data.

The Pce and SWir values calculated from SCAL can be simply characterized as functions of core porosity. Figure 3 shows the exponential and power correlations between core porosity and entry MICP samples in two rock types of I and II respectively. As shown in this figure, regression coefficients, R² are approximately more than 0.9 in the both states indicates that MICPce is inversely proportional to the porosity.

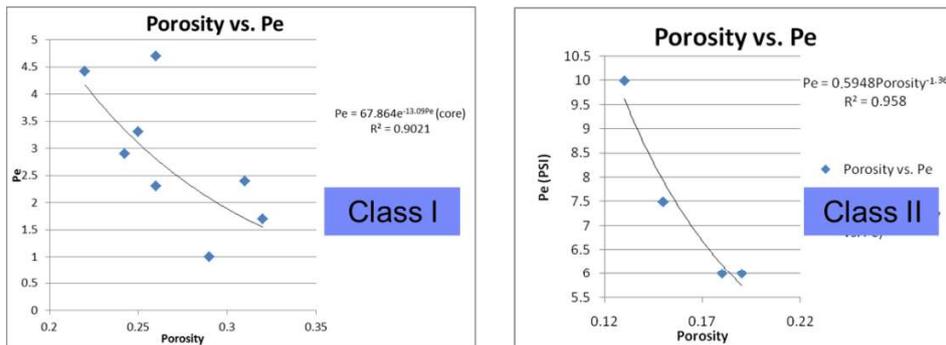


Fig.(3) non-linear regression analysis between core porosity and entry pressure.

As we mentioned above, Swir is one of the effective parameters that straightly influenced the results of calibrated EQR model. But accurately determining of this parameter in the lab circumstances always associated with a high percentage of uncertainty, especially when we

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are using mercury injection tests. Hence, in order to definition of a comprehensive relation between irreducible wetting phase saturation and EQR model, we used petrophysical Swir well logs. For this work, 30 logged wells were selected and then lowest water saturation intervals on Sw well logs have picked against of porosity well logs on corresponding depths (figure 4). These values could be supposed to be Swir with the same porosity and permeability regards to other intervals. Figure 4 illustrates the non-linear correlation between Swir and porosity well logs. Moreover, the statistics of the regression analysis have concisely depicted.

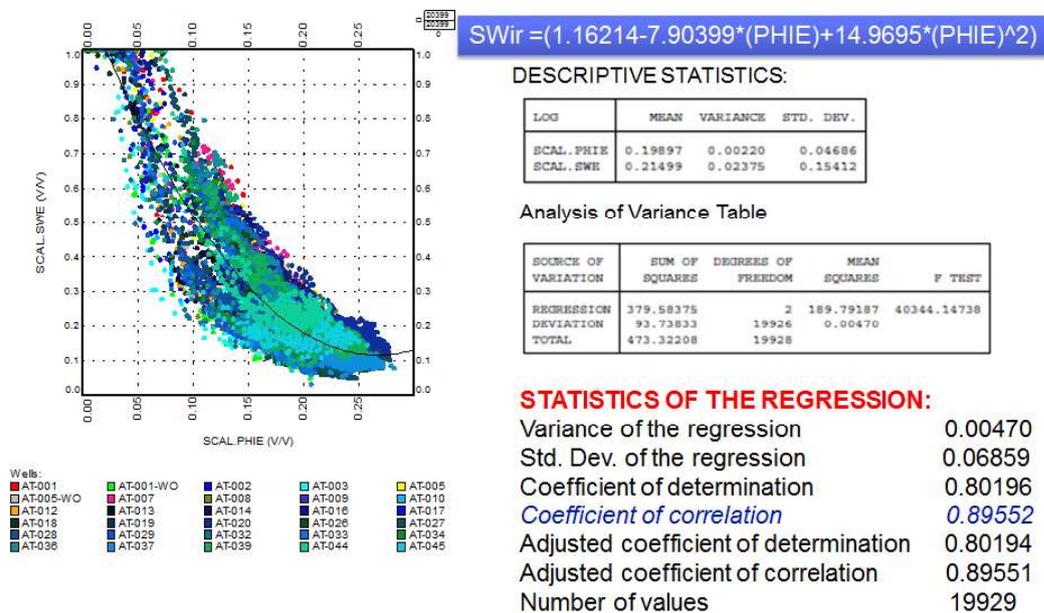


Fig.(94) the non-linear correlation between Swir and porosity well logs and the statistics of the regression analysis.

According to available well test information in the reservoir, the OWC was defined as 3335.6 meter TVDss for Sarvak formation. So with calculation of height of transition zone from following relation we can determine the FWL:

$$FWL = WOC + \frac{144p_d}{\Delta\rho} = 3335.6 + 144 * 2.5 / 21 = 3341.6m$$

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Where FWL = free water level, m, WOC = water-oil contact, m, Pd= averaged threshold pressure, psi, $\Delta\rho$ = difference in pressure gradient between natural reservoir fluids (oil and water) defined by PVT data.

So, using following equation we can easily determined the capillary pressure as a log profiles for all wells:

$$P_c(\log) = \text{HaFWL} * \Delta\rho / 144 = 0.433 * \text{HaFWL} * 0.3363877$$

Where HaFWL in above statement means height above free water level.

With replacing core porosity by effective porosity log on the correlation relations obtained from Figure 3 in each rock types, entry pressure ($P_e(\log)$) can be quantified in terms of log porosity (PHIE). Thus, we have equivalent radius as log profiles through dividing $P_e(\log)$ by $P_c(\log)$ in all wells.

Finally, with rearranging the developed SCAL EQR model using EQR well logs in two different classes of rocks, the water saturation function can be exactly computed in every point of the reservoir. Figure 5 shows the comparison of measured and calculated water saturations in the cored wells so that a perfect match between log and saturation-height model have been achieved.

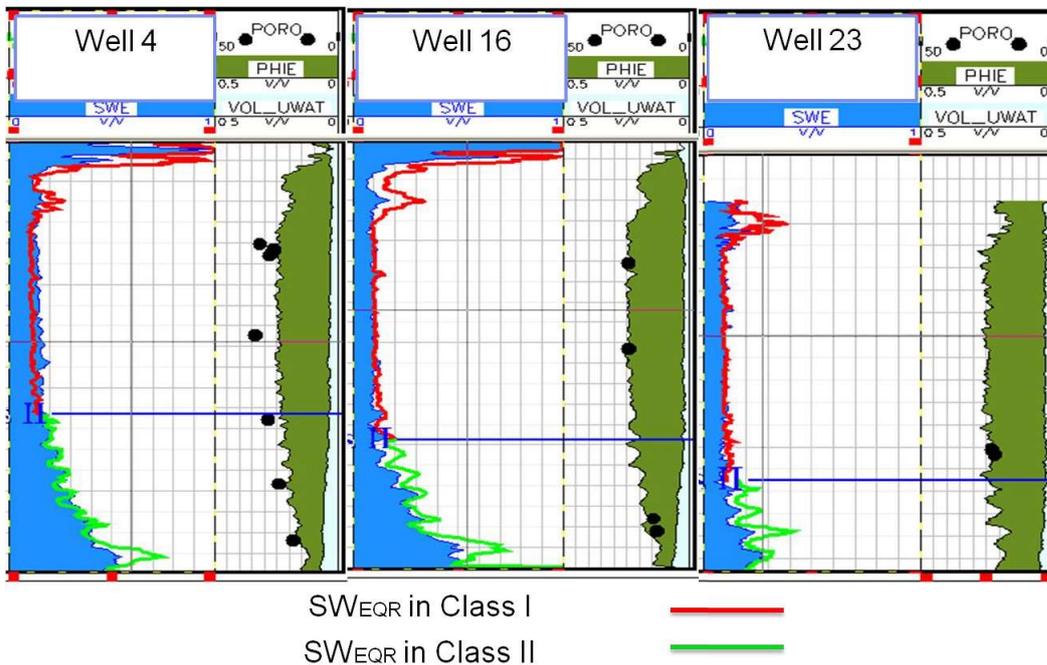


Fig.(5) Comparison of Sw (log) and predicted Sw using EQR method for two different rock types in cored wells.

Results and Discussion

The water saturation mapping have done for in-place hydrocarbon volume approximation and used as input for the next reservoir simulation studies. The main goal of this article was, to express the new saturation height function model for under study oil field and how it was derived from the normalized capillary pressure curves so-called EQR. The work process of saturation height modeling initiates with rock classification of the reservoir pay zone and then a professional curve fitting procedure have applied on SCAL data to optimally generate the parameters of EQR model (P_{ce}, Sw_{ir} and CSF).

It was possible to develop the coherent relationships for each unit of reservoir based on the porosity well logs and SCAL capillary entry pressure. In the same manner we created a porosity dependent function for irreducible water saturation. With replacement of log based EQR to developed EQR model using core lab data leads to determination of initial water

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saturation for all wells of the field. Finally with comparison of the estimated saturation profiles to the interpreted saturation logs a best fit have been achieved.

Residual small divergences between S_w (log) and S_w (EQR) could be result of uncertainty of petrophysical and SCAL data. It is obvious that saturation well logs have calculated using resistivity well logs based on Archi's method or other empirical relationships maybe associated with high degree of uncertainty in some formation. On the other hand, usually special core analysis data in the lab cannot be exactly representative of hydraulically behavior of rock. So the existence of implicit uncertainty in the calibrated EQR model is inevitable in most of the time.

Conclusions:

Modified EQR is a normalized capillary curve matching methodology for saturation height function modeling that is applicable to any reservoir rock type. In the other words, Modified EQR models are capable to perfectly predict water saturation distribution in a wide range of different rocks from low permeability chalks and of carbonate reservoirs to high porosity sandstones.

It is shown that this method can accurately predict the initial water saturation in every point of the reservoir as we have a 3D geo-statics model of porosity with very good match attained in comparison with interpreted saturation well logs.

Nomenclature:

CSF = Capillary Shape Function

D = Depth

EQR = Equivalent Radius

FWL = Free Water Level

OWC = Oil Water Contact

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P_c = Capillary pressure

P_{ce} = Capillary entry pressure

S_{nw} = Non-wetting phase saturation

S_{nw} = Normalized non-wetting phase saturation

S_{wir} = Irreducible water saturation

TV DSS = True vertical depth Sub Sea

MICP = mercury injection capillary pressure

mD = Mili-darcy

$\Delta\rho$ = difference in fluids density

P_{eCalib} = Calibrated Capillary entry pressure

$S_{wirCalib}$ = Calibrated Irreducible water saturation

PHIE = Effective porosity well log

S_w = Water saturation

HaFWL = Height above free water level

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