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Analytical Model for Detection the Tilt in Originally Oil Water Contacts

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Abstract

Many carbonate reservoirs in the world show a tilted in originally oil-water contact (OOWC) which requires a special consideration in the selection of the capillary pressure curves and an understanding of reservoir fluids distribution while initializing the reservoir simulation models.

An analytical model for predicting the capillary pressure across the interface that separates two immiscible fluids was derived from reservoir pressure transient analysis. The model reflected the entire interaction between the reservoir-aquifer fluids and rock properties measured under downhole reservoir conditions.

This model retained the natural coupling of oil reservoirs with the aquifer zone and treated them as an explicit-region composite system; thus the exact solutions of diffusivity equation could be used explicitly for each region. The reservoir-aquifer zones were linked by a capillary transition zone that reflected the pressure difference across the free water level.

The principle of superposition theorem was applied to perform this link across the free water level to estimate the reflected aquifer pressure drop behavior that holds the fluid contacts in their equilibrium positions.

The results of originally oil water contact positions generated by the proposed model were compared with data obtained from a carbonate oil field; the results given by the model showed full agreement with the actual field data.

Keywords: Capillary pressure, Tilted oil water contact

Introduction

Many carbonate reservoirs in the world show a tilted in OOWC; an inaccurate determination for this tilting causes erroneous results in estimating the original oil in place (OOIP) in reservoir simulation process, and provides inadequate water flooding schemes while field development process, would affect reservoir recovery process and reserve prediction.

The actual cause for the tilt of OOWC is still under investigation. The difficulties in studying the OOWC tilt related to the lack of flank wells intersecting the OOWC. In addition, most of the available information coming from edge wells in areas of high cristal production resulting in dynamic oil water contact (OWC), not OOWC. This OOWC differs from the dynamic OWC that is related to the pressure gradient caused by oil production and subsequent pressure drop in the producing area which vary along the oil-water interface and causing the water to move with varying speeds in the different parts of the reservoir; this causes a distortion in the OWC.

Previously, a wide explanation for the tilt was a huge regional dynamic aquifer to what recently has established the cause for the regional temperature gradient variation [1]. Several theories were presented in the past to investigate the tilted OOWC, but in fact none were able to account successfully for the origin of this phenomenon. However, Stenger [2] shows that the geothermal gradient is a controlling parameter of the aquifer salinity and this affects the gradual change in oil-water densities. Shawket G.Ghaidan et al. [3] stated that capillary pressure reflects the interaction of rock and the fluids filling these pores. The measurements of capillary pressure must ideally perform in reservoir conditions to reflect the actual field analysis, but unfortunately one is extremely difficult and is usually done by injecting mercury at ambient conditions. However, the experience showed that either capillary pressure measured in the laboratory or capillary pressure converted to reservoir conditions may not match the log derived Sw - Pc data which also has an accuracy of +/- 10% in best and may be as high as +/- 20%. [3].

Anderson [4] also confirmed that the capillary pressure - saturation relationship depends on the interaction of wettability, pore structure, initial saturation, and saturation history. No simple relationship exists that relates the capillary pressure determined at two different wettabilities. Therefore, the most accurate measurements are made with cores that have native reservoir wettability.

Majid Hassanizadeh et al. [5] stated that although the processes that determine the distribution of fluid phases in porous media are extremely complicated. The main theoretical and practical tool currently used to quantify the capillary pressure function is an empirical relationship between capillary pressure and saturation and as such, it lacks a firm theoretical foundation. This simple empirical model is implicitly assumed to account for all effects and processes that influence the equilibrium distribution of fluids, such as surface tension, presence of fluid–fluid interfaces, wettability of solid surfaces, grain size distribution, and microscale heterogeneities. All of these effects are essentially lumped into the capillary pressure and saturation relationship. In fact, there is ample theoretical and experimental evidence that this simple relationship is not unique, but it depends on the flow dynamics; it depends on both the history and the rate of change of saturation. The dependence of capillary pressure–saturation curves on the history of flow is known as capillary pressure hysteresis this is a well-known effect and has been the subject of extensive investigations. The dependence of capillary curves on the rate of change of saturation is due to dynamic effects.

Theories Used in Initialization of OOWC

Due to the variance of the theories made to explain the reasons of tilted OOWC, Hsueh et al. [1] suggested four different methods that could be used in initializing the OOWC as follows:

1- Initialization with capillary pressure correction: This method provides a correction term for capillary pressure added to the general definition of capillary pressure to balance the difference in oil column thickness with respect to the free water level.

2- Initialization with specified water saturation: This method suggests that if there is a large saturation contrast in the vertical direction, it may cause instability at time zero of reservoir saturation initialization; this instability may extend over the course of the history match.

3- Initialization by equilibrium region: This method is simple in application; the reservoir area is divided into two equilibrium regions with two different OWC. The disadvantage of this method is that it is not applicable to account for more than one tilt direction.

4- Initialization by dynamic injection-production method: This method suggests using pseudo injection/production wells located at the sides of the tilt to artificially create the tilted OWC. The pseudo injection well is located at the side of high water column of the tilt, while the pseudo production well is located at the lower water column of the tilt.

Image Theory

The most powerful techniques in reservoir engineering is the principle of image theorem that can be applied to removing the restrictions that have been imposed on various forms of solution. The principle of image theorem says that the response of the system to a number of events is exactly equal to the sum of the responses to each of the events as if they were present by themselves.

It is well known that the capillary pressure holds the fluid interfaces at their equilibrium positions unless a pressure disturbance may occur at the contacted free fluid interfaces [6]. Thus, the new theory of measuring the dynamic capillary pressure under reservoir conditions suggests creating reservoir pressure drop pulse that is usually performed throughout conventional well test analysis.

Therefore, it is essential to formulate dynamic capillary pressure model in an appropriate way due to its importance in reservoir simulation and engineering applications; in order to reduce the complexity, the formulation of an accurate analytical dynamic capillary pressure model in which the created reservoir pressure drops moving between two different fluid mediums (oil and water) could be analyzed by treating each fluid-phase zone as explicit single-phase zone that takes its own fluid and rock properties, as already adopted by Layne et al. [7]; hence, the reservoir-aquifer zones are linked across the free water level (zero capillary pressure) by a capillary transition zone that is balancing the pressure difference across the free water level.

Hence, the free water level could be considered as a no-flow boundary and the reservoir may behave as an infinite acting reservoir as well as the free water level still not affected by the created reservoir pressure drops. Based on this principle, the pressure difference across the free water level must remain constant while the pressure transient flow period which reflects the dynamic capillary pressure across the free water level representing the initial transition zone thickness of height depends on the density difference between the oil and water.

Thus, the exact solution could be generated using the principle of image theorem throughout reflecting the created reservoir pressure drops at the free water level to estimate the reflected pressure drops in a manner exactly identical to the procedure used to estimate the reservoir pressure drops for a well bounded by a no-flow boundary; therefore, this solution is valid only during the pressure transient flow period. Hence, both of the created and the reflected pressure drops should exhibit transient flow behavior.

Since, based on the principle of image theorem, the exact solution to estimate the pressure difference across the free water level is exactly equal to the sum of the responses for the reservoir and aquifer zones, taking into consideration that the solution of Van-Everdingen and Hurst [8] for infinite-radial flow will represent the created reservoir pressure drops encountered due to oil production activity, and Keith Coats [9] exact solution to represent the imposed reflected pressure drops encountered at free water level.

The aquifer will respond to the created reservoir pressure drops by an imposed reflected pressure drops that depend on its own water and rock properties. Hence, both of the created and the imposed reflected pressure drops should exhibit transient flow behavior, as well as the created reservoir pressure drops have not reached the free water levels yet.

Estimation Dynamic Capillary Pressure

The main theoretical and practical tool currently used to quantify the capillary pressure function is only an empirical simple function that lacks meeting all parameters affecting capillary pressure-saturation relationship as given by Eq. 1.

$$P_c = P_o - P_w \qquad \ldots(1)$$

Where $(P_o and\ P_w)$ are the pressures exerted at the free water level by both of reservoir fluid and aquifer water zones, respectively.

Adding and subtracting the initial reservoir pressure (P_i) to the right hand side of Eq. 1 and arranging it which could be rewritten as follows;

$$P_c = (P_i - P_w) - (P_i - P_o) \qquad \ldots(2)$$

The term $(P_i - P_o)$ represents the created reservoir pressure drop behavior during transient flow period, which could be estimated using Van-Everdingen and Hurst [8] for infinite radial flow solution; while, $(P_i - P_w)$ represents the imposed reflected pressure drops by the aquifer zone, which could be estimated using Keith [9], for two dimensional flow solution.

The numerical results for a computer program prepared to estimate the pressure difference across the free water level for many different hypothetical systems show constant pressure difference behavior between the created and the reflected pressure drops during the pressure transient solutions as shown in Fig. 1; however, the values of pressure difference depend entirely between the contacted rock and fluid properties (Darcy's law).

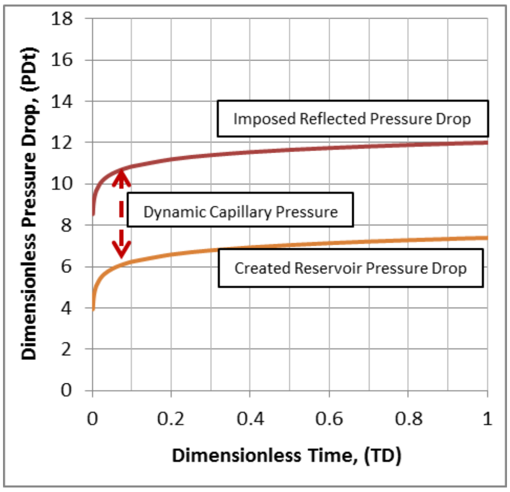

Fig. 1, Schematic drawing shows the constant difference between the created and reflected pressure drops denoting the dynamic capillary pressure across the free water level

As commonly used in reservoir performance analysis, the pressure drop behavior could be represented in dimensionless form. Thus, the capillary pressure term could also be converted to dimensionless capillary pressure form. Therefore, Eq. 2 can be expressed in dimensionless form as follows:

$$P_{cD} = P_{Dw} - P_{Do} \quad ...(3)$$

Where(P_{cD}) is the dimensionless dynamic capillary pressure.

Hence, the dynamic capillary pressure is zero at the free water levels; thus Equation 2 could be written at the water free level as follows;

$$P_{Dw} = P_{Do} \quad ...(4)$$

Using Van-Everdingen and Hurst [8], for infinite radial flow solution for the created reservoir pressure drops expressed by the following expression:

$$P_{Do} = 0.5\,[ln(T_{Do}) + 0.809] \quad ...(5)$$

Where (T_{Do}) represents the dimensionless time provided by the following expression as given by John Lee et al. [10] and Tarik Ahmed [11]:

$$T_{Do} = \frac{0.006328\,K_o.t}{\varphi_o \mu_o C_o r_w^2} \quad ...(6)$$

Where (φ_o and K_o) are the reservoir porosity and permeability ($\mu_o and\ C_o$) are the reservoir fluid viscosity and compressibility, respectively, (r_w) is the producing well radius, and (t) is the producing time.

While, the reflected pressure drops by the aquifer zone exhibit two dimensional flow in radial and vertical directions using the solution of Keith Coats [9], which can be written as follows:

$$2\,\frac{K_w}{K_h}\,\frac{H_w\sqrt{K_h}}{r_e.\sqrt{K_v}}\left[A + \frac{1}{4M}\,ln(T_{Dw})\right] = P_{Dt} \quad ...(7)$$

Where (T_{Dw}) represents the dimensionless time provided by the following expression which is written by using aquifer zone properties as follows:

$$T_{Dw} = \frac{0.006328\,K_w.t}{\varphi_w \mu_w C_w r_w^2} \quad ...(8)$$

M is dimensionless aquifer size, which is expressed as follows [9, 11]:

$$M = \frac{H_w\sqrt{K_h}}{r_e.\sqrt{K_v}} \quad ...(9)$$

A is a constant that depends on aquifer size as given by Keith Coats [9].

The final form of Keith Coats [9] model given by (7) was arranged by Al-Sudani [12] to be applicable in all reservoir sizes as follows:

$$[2A.M + 0.5\ ln(T_{Dw})] = P_{Dw} \quad ...(10)$$

Where P_{Dt} is the dimensionless aquifer pressure drops at free water level.

$$P_{Dw} = \frac{K_h}{K_w} P_{Dt} \quad ...(11)$$

Substituting Eqs. 5, 6, 8 and 10 in Eq. 3 will generate the following expression:

$$P_{cD} = \left[0.5[2A.M + o.5\,ln\left(\frac{0.006328\,K_w.t}{\varphi_w \mu_w C_t r_w^2}\right)]\right] - \left[0.5[ln\left(\frac{0.006328\,K_o.t}{\varphi_o \mu_o C_o r_w^2}\right) + 0.809]\right] \quad ...(12)$$

The values of (A) as given by Keith Coats [9] behave as shown in the following expression:

$$A = 0.5M^{-0.8} \quad ...(13)$$

Substituting Eq. 13 in 12 yields the following:

$$P_{cD} = \left[0.5[M^{0.2} + o.5\,ln\left(\frac{0.006328\,K_w.t}{\varphi_w \mu_w C_t r_w^2}\right)]\right] - \left[0.5[ln\left(\frac{0.006328\,K_o.t}{\varphi_o \mu_o C_o r_w^2}\right) + 0.809]\right] \quad ...(14)$$

Simplifying Eq. 14 yields the following:

$$P_{cD} = ln\left(\frac{0.006328\, K_w.t}{\varphi_w \mu_w C_w r_w^2} * \frac{\varphi_o \mu_o C_o r_w^2}{0.006328\, K_o.t}\right) + (M^{0.2} - 0.809) \quad \ldots(15)$$

And;

$$P_{cD} = ln\left(\frac{K_w}{K_o}\frac{\varphi_o \mu_o C_o}{\varphi_w \mu_w C_w}\right) + (Y) \quad \ldots(16)$$

Where (Y) is the effect of aquifer size on capillary transition zone that is expressed by:

$$Y = (M^{0.2} - 0.809) \quad \ldots(17)$$

For further simplification, it is assumed that the displaced and displacing fluid zones have the same porosities; thus, Eq. 16 could be rewritten as follows:

$$P_{cD} = ln\left(\frac{K_w}{K_o}\frac{\mu_o C_o}{\mu_w C_w}\right) + (Y) \quad \ldots(18)$$

Eq. 18 provides general expression for dimensionless dynamic capillary pressure term performed under reservoir conditions. The expression can be converted to its dimensional form throughout multiplying the dimensionless values by $(\Delta P/P_D)$:

$$\frac{\Delta P}{P_D} = \frac{141.2 * Qo\ \mu o\ Bo}{Ko\ Ho} \quad \ldots(19)$$

Thus, the dynamic capillary pressure term could be written as follows:

$$P_c = P_w - P_o = \frac{141.2 * Q_o\ \mu_o\ B_o}{K_o\ H_o}\ [P_{cD}] \quad \ldots(20)$$

However, the transition zone thickness is the function of the pressure difference across the free water level and the density difference between oil and water, which is commonly expressed as given by [1 and 5] as follows:

$$H_{tz} = \frac{144\ P_c}{g_c.\Delta\rho} \quad \ldots(21)$$

Where, $\Delta\rho = (\rho_w - \rho_o) \quad \ldots(22)$

While (H_{tz}) and (P_c) represent the initial transition zone thickness and the dynamic capillary pressure, respectively and (g_c) is conversion parameter that equals =32.17 $ft.ib_{mass}/ib_{force}.sec^2$.

Application of this method requires only one conventional drawdown well test analysis and some simple laboratory measurements for oil and water viscosity and compressibility at initial reservoir conditions to estimate accurately the dynamic capillary pressure rather than performing some complicated laboratory measurements for capillary pressure which in due course cannot be done at reservoir conditions.

Results and Discussion

The presented model given in Eq. 20 which is derived from the simple definition of capillary pressure shown in Eq. 1 involves all rock and fluid properties for both of reservoir and aquifer zones. Moreover, all of the properties can be measured under reservoir conditions as the reservoir permeability can be obtained from well test analysis; while, the aquifer's zone permeability can be estimated from injectivity test or using Voigt's [13] model. Then, both of reservoir and aquifer viscosity and compressibility can be estimated from PVT data at actual reservoir pressure and temperature. Since, the developed model reflects the real interaction between all rock and fluid properties, and will eliminate the logging analysis and coring works in determining the fluid contact positions.

Figs 2, 3 and 4 were built for a hypothetical reservoir-aquifer system as given in Table 1; the effects of reservoir and aquifer permeabilities, reservoir thickness and aquifer size properties were verified to take full knowledge for the controlling parameters on dynamic capillary pressure. Investigating these figures show the emphasized effect for reservoir characteristics in increasing the dynamic capillary pressure which led for thicker transition zone than that observed for aquifer characteristics.

Table 1: Reservoir-Aquifer hypothetical system variables

	Fig. 2	Fig. 3	Fig. 4
Q_o, B/D	5000	5000	5000
K_o, md	Variable	600	600
K_w, md	Variable	120	120
μ_o, cp	2	2	2
μ_w, cp	1	1	1
ρ_o, Ib/ft^3	52.1	52.1	52.1
ρ_w, lb/ft^3	63.2	63.2	63.2
H_o, ft	90	Variable	90
H_w, ft	80	80	80
B_o,RB/STB	1.2	1.2	1.2
B_w,RB/STB	1.01	1.01	1.01
C_o, Psi^{-1}	8*10^{-6}	8*10^{-6}	8*10^{-6}
C_w, Psi^{-1}	2*10^{-6}	2*10^{-6}	2*10^{-6}
r_w, ft	0.25	0.25	0.25
φ_r	0.2	0.2	0.2
φ_a	0.2	0.2	0.2
S	0.0	0.0	0.0
M	0.005	0.005	Variable
S_{wc}	0.2	0.2	0.2

It is noticed that the aquifer permeability has an adverse effect on dynamic capillary pressure compared with the effect of reservoir permeability as shown in Fig. 2; this conclusion gives an accurate thorough explanation for the variation in oil water contact positions than previously acknowledgment, which only relates to the phenomenon for reservoir permeability variation. The reason for the shortage explanation of tilt OOWC, can be attributed for unavailable exact theoretical model in the literature to estimate the dynamic capillary pressure that involve all influencing reservoir and aquifer properties. While Figs 3 and 4, respectively, show the adverse effect for reservoir thickness and aquifer sizes on dynamic capillary pressure. This can be attributed for the reduction in reservoir pressure props. Hence, it can be stated that same effects for both reservoir and aquifer's fluids properties (viscosity and compressibility) on dynamic capillary pressure, as both of them affect the created and imposed reflected pressure drops.

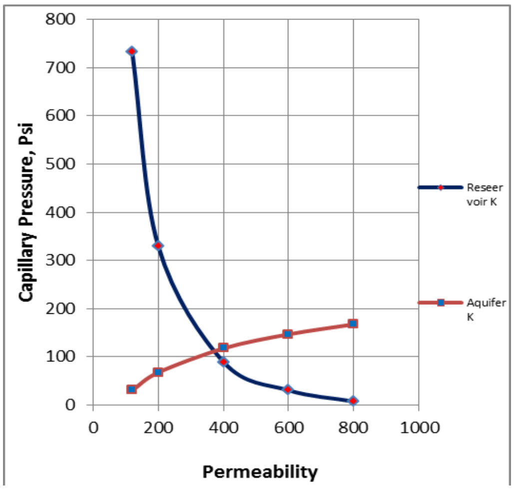

Fig. 2: Reservoir and Aquifer permeability effects on capillary pressure

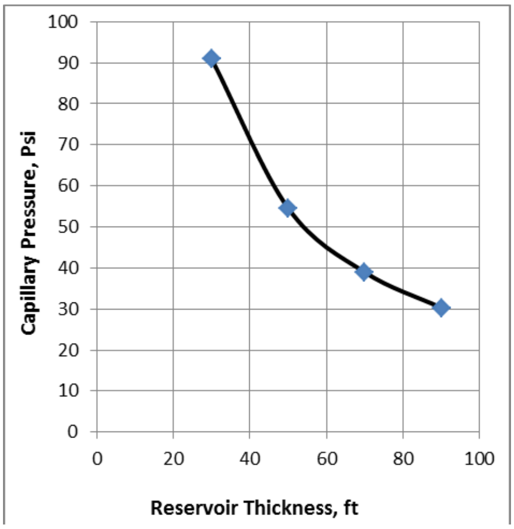

Fig. 3: Effect of reservoir thickness on capillary pressure

Meanwhile, the tilt in originally oil-water contact has been studied for Iraqi carbonate oil field producing from two main reservoirs under different reservoir-aquifer properties as given in Appendix-A; the generated results from the current model were compared with the actual field data that showed very identical results.

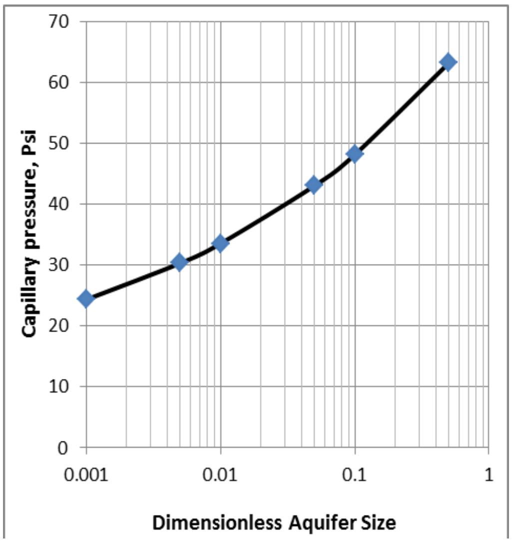

Fig. 4: Effect of Dimensionless aquifer size on capillary pressure

Conclusions

The presented model provides the real measurements and full explanation without any limitation for the tilts in OOWC under actual reservoir conditions. This method uses only the conventional well test analysis performed in reservoir. Moreover, the theory has a lot of advantages which could be stated as follows;

1- The analysis provides the actual measurements of the tilt in OOWC.
2- It is directly applied using reservoir pressure transient analysis and no experimental laboratory works needed, since it is a cost effective procedure when performing some complicated experiments.
3- This method could be applied in any position within the entire reservoir area, since it could provide the tilt of OOWC in all directions.
4- The model will assist in accurately evaluating the originally hydrocarbon in place throughout determining the transition zone intervals and saturation distribution.
5- The model can be considered an easy tool in estimating the OOWC in reservoir simulation studies.

Nomenclature

Symobile	Difintion	Unit

B_o Oil formation volume factor RB/STB

BOPD Barrel oil per day.

C_w Total Aquifer compressibility Psi^{-1}

C_o Total reservoir compressibility Psi^{-1}

FWL Free Water Level

g_c Conversion constant =32.2

H_o Oil reservoir column thickness, ft

H_{tz} Transition zone thickness, ft

K_h Aquifer zone permeability in horizontal direction.

K_o Reservoir zone permeability

K_v Aquifer zone permeability in vertical direction.

K_w Absolute aquifer zone permeability

M Dimensionless Aquifer size.

P_c Capillary pressure, Psi

P_{cD} Dimensionless capillary pressure

P_i Initial reservoir pressure, Psi

P_w Aquifer pressure at FWL Psi

P_o Reservoir pressure at FWL Psi

P_D Dimensionless pressure drop

P_{Do} Dimensionless reservoir pressure drop

P_{Dt} Dimensionless reflected pressure drop occurs in the free water level

P_{Dw} Modified dimensionless reflected pressure drop occurs in the free water level

Q_o Oil flow rate, STB/Day

r_w Well radius, ft

t Production time, days
T_D Dimensionless time
T_{Dw} Dimensionless time calculated using aquifer zone properties
T_{Do} Dimensionless time calculated using reservoir zone properties
Y Aquifer size effect on capillary zone.

Greek Symbols

μ_o Oil viscosity Cp
μ_w Water viscosity Cp
ρ_o Oil density Ib.m/ft^3
ρ_w Water density Ib.m/ft^3
$\Delta\rho$ Density difference Ib.m/ft^3
φ_o Reservoir porosity
φ_w Aquifer porosity

References

1- Hsueh P.T., Pham T.R. and Bu-Hulaigah E.H."A Review of different initialization and history matching a reservoir model with tilted oil water contact".SPE-53373 – 1999.
2- Stenger B.A." Regional Temperature Gradient: A Key to Tilted OOWC". SPE-53197, 1999.
3- Shawkat G. Ghaidan, Bertrand M. Thiebot and Douglas A Boyd."Modeling and Validation of Initial Water Saturation in the transition Zone of Carbonate Oil Reservoirs". SPE- 88756, 2004.
4- Anderson,W.G.: "Wettability Literature Survey – Part 4: Effects of Wettability on Capillary Pressure", JPT (Oct. 1987) 1283-1300.
5- Hassanizadeh SM, Oubol Oung, Sabine Manthey;" Laboratory Experiments and Simulations on the Significance of Non-Equilibrium Effect in the Capillary Pressure-Saturation Relationship", Unsaturated Soils: Experimental Studies, Springer Proceedings in Physics Volume 93, 2005, pp 3-14.
6- Al-Khalifah, A.J.A.; Odeh, A.S.: "Well Test Analysis in Oil Reservoirs with Gas Cap and/or Water Aquifer". SPE-19842, paper presented at the 64th annual technical conference and exhibition of SPE held in San Antonio,Tx, Oct.8-11, 1989.
7- Layne M.A., Numbere D.T. and Koederitz L.F.: "Analytical Solution to Predict the Performance of Gas Reservoirs under Water Drive" SPE-26669, Paper Presented at 68th Annual Technical Conference and Exhibition of SPE Held in Houston, Texas 3-6 Oct. 1993.
8- Van-Everdingen, A.F. and Hurst, W.; "The Application of Laplace Transformation to Flow Problems in Reservoirs", Trans. AIME (1949) Vol. 186, 305.
9- Keith H. Coats; "A Mathematical Model Water Movement about Bottom-Water Drive Reservoirs." SPE-160, paper presented at 36th annual fall meeting of SPE, Oct.8-11, 1961, in Dallas.
10- John-Lee, John B. Rollins, John P. Spivey "Pressure Transient Testing" SPE Textbook Series, Texas.2003.
11- Tarik Ahmed, Paul D. McKinney; "Advance Reservoir Engineering" Elsevier, 2005, Chapters (1 and 2).
12- J.A. Al-Sudani," Prediction the Future Performance of reservoir Fluids Movement under Combined Drive Mechanism" Ph.D. Thesis submitted to Uinv. Of Baghdad, Pet. Eng. Dept. May, 2009.
13- Voigt, H.D. and Astl, A.; "Determination of Permeability from Responses in Aquifer Wells". SPE-16996, 1987.

APPENDIX-A:

Field Example: It is an Iraqi carbonate oil field given by Al-Sudani [12] produced from two main reservoirs under bottom water drive aquifer. The reservoir and aquifer zones properties are listed as shown in Tables A-1 and A-2, respectively.

Other reservoir and aquifer fluids properties are as follows; (C_o=8.95*10^{-6} Psi^{-1}, μ_o=0.65 Cp, B_o=1.46 RB/STB) and (C_w=2.5*10^{-6} Psi^{-1}, μ_w=0.705 Cp, B_w=1.02 RB/STB), app. oil density=53.4 Ib/ft^3, approximate water density=63 Ib/ft^3. Approximate dimensionless aquifer size = 0.005.

Four wells penetrating the main reservoirs were selected in this test representing the west and east sides of the reservoir; the flow rates of these wells are listed in Table A-3.

Required: Estimation of Capillary transition zone thickness to predict the tilt in OOWC.

Table A-1: Main reservoir characteristics

Unit	A	D
Net thickness (ft)	25	125
φ	0.21	0.24
K- md	580	1115

Table A-2: Aquifer characteristics

West			East	
Unit	A	D	A	D
K_w – md	1381	2297	305	1165
φ	0.32	0.23	0.14	0.2
Thick- ft	92	100	43	110

Table A-3: Well Production of Oil in units A and D (BOPD)

Reservoir	West Region	East Region
A	8300	4100
D	7875	5155

Solution:

A computer program on Excel sheet was prepared to be used in estimating dynamic capillary pressures and the transition zone thickness based on the derived analytical model represented by Eqs. 18, 20 and 21; the results are listed as shown in Table A-4;

These results obtained by the new model show high tilted OOWC that exists between west-east regions for units (A and D); the results confirm this carbonate field of OWC characteristic and may provide the best explanation for the tilted OOWC in some carbonate reservo

irs which is still under investigation.

Table A-4: Calculated values of capillary pressure and transition zone thickness

	(A); East	(A); West	(D); East	(D); West
P_{cD}	1.15379	4.63114	2.7346	4.2977
P_c, Psi	43.716	355.221	13.553	32.539
H_{tz}, ft	20.3836	165.630	6.3195	15.1722

The results of this field data exactly show the titled in originally oil-water contact from west to east, especially in reservoir unit (A) due to the high variation in rock and fluid properties with the aquifer, compared with what is observed in reservoir unit (D). The results confirm the actual tilts in OOWC from west to east in both units; therefore, the new methodology may explain the reasons beyond this phenomenon which is still under investigation by some authors such as Hsueh [1].