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The use of material balanced equation to determine the oil water contact of an oil reservoir

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Abstract

The oil water contact of an oil reservoir can be determined using some geophysical well logs. However, some of the methods might not be accurate. Therefore the material balanced equation which is an accurate means of formation evaluation is critically analysed in this study and then used to determine the oil water contact of oil reservoirs A and B in the Niger Delta Basin of Nigeria.

1.0 Introduction

It is often desirable to make dependable estimates of the initial hydrocarbons in a reservoir and to be able to predict the future reservoir performance and the ultimate Hydrocarbon recovery from the reservoir.

Numerous procedures have been proposed and employed for estimating hydrocarbon initial Oil in place [3]. The most commonly used is volumetric method as stated by [6]. However, it has become both practical and popular to confirm such estimates by material balance equations. The type of material balance equation used in such estimates is similar to that used in many other fields of Engineering for quantity and quality estimate and control. In the simplest form, the material balance equation can be written as:

Initial volume = volume remaining + volume removed.

Since oil, gas and water are present in petroleum reservoirs, it is seen that the material balance equation can be written for the total fluids or for any one of the fluids present.

A concept of material balance for the estimation of hydrocarbon in under ground reservoirs was presented by [11]. The principal improvement in application of the equation in practice has been made possible through refinement on measurements and the continuing efforts of reservoir Engineers to expand the equation to encompass the reservoir rock and its contents.

Over the years, well log interpretation has been based on finding the amount of water in a formation, deducing from that quantity whether or not hydrocarbons are present, and, if, so determining the volume.

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These techniques have been based on the resistivity and/or pulsed neutron captures contrast between water and oil. In both measurements the contrast are at their minimum when the salinity of the water phase is low. Neither method can accurately determine water saturation when the water salinity is near zero.

What is obviously needed is a logging device that measures the bulk volume of water or oil in a formation without any dependence on the salinity of the formation water. Several types of measurements are available to the industry in theory if not in actual practice. One of these salinity-independent measurements is an analysis of the abundance of carbon and oxygen atom.

The theory associated with the carbon and oxygen measurement has been known for many years, but only within the last several years has technology improved to allow a reliable measurement outside the laboratory environment (Roscoe et al [8]. Oil companies, research groups and, later, service companies introduced prototype tools, which were successful. There are now a few logging companies with tools, which commercially measure the Carbon – Oxygen ratio (COR).

The purpose of this study is to estimate the oil water contact using a mathematical approach. This method is more accurate than other methods and by far cheaper [2]. This mathematical approach is not affected by water salinity. It is therefore a breakthrough in reservoir engineering.

Frank and Philips, [3] examined the method of using material – balance equation for the determination of water influx using aquifer models approach. The calculated water influx from a reservoir that has produced for some time is substituted into the modified material balance to derive the new contact. However this method could not determine water saturation when the water salinity is near zero.

Gilchrist, et al [4] examined the method of measurement and interpretation to determine bulk volume of water or oil in a formation without any dependence on the salinity of the formation water. This was perhaps an improvement on other previous researches in terms of accuracy. This method however is very expensive.

Oliver et al, [6] examined the use of carbon / oxygen logging instrument as a pulsed neutron device which measures the energy and intensity of gamma rays resulting from neutron irradiation of the formation. This information can be related to the relative abundance of particular elements in the formation (such as carbon, oxygen silicon and calcium). Ratios formed from the relative abundance of these elements are particularly useful in identifying formation lithology, porosity, and fluid content.

2.0 Theory

2.1.1 Oil-water contact

The oil water contact is selected on the core or log as the point at which the oil saturation of the sample decreases and the water saturation increases. This is the oil - water contact defined as the level below which the fluid production is 100% water.

Unfortunately, not all wells drilled penetrate the water-bearing portion of the formation. It thus becomes necessary to determine the limits of the Oil-water contact from a merger set of data. The transition between Oil and water is defined as the Oil water contact (OWC).

$$V_w 0 \cdot 00624k\left(p_w - \rho_0\right)\frac{\partial h / \partial x}{144\mu}$$

where

x = distance along horizontal axis
p_w = Density of water

ρ_o = Density of oil
V_W = Velocity of water
$\partial h/\partial x$ = Slope of contact.
K = permeability
μ = Viscosity

From the equation above, it may be noted that the greater the velocity of the water, the greater the slope of the Oil-water contact.

In the determination of the position of the oil-water contact, it is suggested that all open hole drill-stem tests, production and completion tests, core analysis and log data be plotted on the structural map of the structure.

2.1.2 Reservoir description

Below is a brief description of the two Reservoirs utilized in this study.

2.1.2.1 Reservoir A

The Reservoir for well A is silty, slightly gravelly, moderate to well sorted, with loosely consolidated sand. The Reservoir was laid down in a Bathyal environment and represents a delta prograding Parasequence whose top paleo-channel sand may have been eroded.

2.1.2.2 Reservoir B

This Reservoir sand is moderate to well sorted with loosely consolidated stacks of coarsing upward parasequences. It is inferred to have been laid down during a possible late high system tract (HST) and early low system track (LST). The depositional environment is middle nerific. These two Reservoirs under study contain only two fluids i.e. water and oil, hence Reservoir is described as an undersaturated Reservoir. Since only two fluids are present (water and oil), their relative rates of flow are determined by their relative viscosity and their relative permeability.

The permeability of the two reservoirs under study is 3 - 5 Darcy. The porosity is presented as 0.13 for Reservoir A and 0.30 for Reservoir B respectively.

There are several ways for determining the oil in place. To do this, the type of reservoir must be known so that the formula and parameters can be determined. Below are some of the methods used in the determination of the oil in place: Volumetric method, Material Balance Equation, Decline Curve analysis and Empirical correlation.

2.1.2.3 Volumetric Reservoir

This method is based on log and core analysis data to determine the bulk volume, the porosity and the fluid saturations, and upon fluid analysis to determine the oil volume factor. Let N denote the stock tank oil in place, then

$$N = \frac{7758Ah\phi(1-S_w)}{B_w} \tag{2.1}$$

where

A = cross sectional area of reservoir
h = height (thickness) of reservoir
ϕ = Porosity of the reservoir rocks
S_w = Water saturation
B_{oi} = Initial formation oil volume factor

For oil reservoirs under volumetric control, since there is no water influx to replace the produced oil, it must be replaced by gas whose saturation increases as the oil saturation decreases. If S_g is the gas saturation and B_o the oil volume factor at abandonment, then at abandonment:

$$N = \frac{7758\phi(1-s_w)}{B_{oi}}. \qquad (2.2a)$$

$$N = \frac{7758\phi(1-s_g-s_w)}{B_o} \qquad (2.2b)$$

where N_r is the recoverable oil in the reservoir.
If we denote the recovery by $N - N_r$, then clearly

$$N - N_r = 7758\phi\left[\frac{(1-s_w)}{Boi} - \frac{(1-s_g-s_w)}{B_o}\right] \qquad (2.3)$$

and the recovery factor is given by

$$\text{Recovery factor} = \frac{N-N_r}{N} = 1 - \frac{(1-s_g-s_w)}{B_o}\frac{B_{oi}}{(1-s_w)} = 1 - \frac{(1-s_g-s_w)}{(1-s_w)}\frac{B_{oi}}{B_o} \qquad (2.4)$$

2.1.3 Water drive reservoir

Due to the water influx, the pressure is maintained and therefore the oil formation volume factor remains approximately constant and so B_{oi} is equal to B_o at abandonment pressure. Hence, denoting $1- s_g - s_w$ by s_{or}, equation (2.2b) becomes :

$N_r = \frac{7758\phi(s_{or})}{B_{oi}}$, where s_{or} = Residual oil saturation. Hence

$$N - N_r = \frac{7758\phi(1-s_w)}{B_{oi}} - \frac{7758\phi(s_{or})}{B_{oi}} = \frac{7758\phi}{B_{oi}}(1-s_w-s_{or})$$

Recovery factor

$$\frac{N-N_r}{N} = \frac{7758\phi}{B_{oi}}(1-s_w-s_{or})\, 7758\phi(1-s_w)\Big/B_{oi} \quad \frac{N-N_r}{N} = \frac{1-s_w-s_{or}}{1-s_w} \qquad (2.5)$$

2.1.4 Material balance equation

Material balance equation is used to confirm the value obtained from volumetric method. It is simply a volume balance, which equates total production to the difference between the initial volume of hydrocarbons in the reservoir to the current volume.

2.1.4.1 Material balance for volumetric under saturated oil reservoir.

The term volumetric depletion applied to the performance of a reservoir means that as the pressure declines, due to production, there is an insignificant amount of water influx into the reservoir from the adjoining aquifer. This in turn implies that the reservoir volume occupied by hydrocarbons will not decrease during depletion.

Amount of oil remaining at surface condition = $(N - N_p)$

where N_P = Cummulative oil produced

Amount of oil remaining at Reservoir Condition = $(N - N_p)B_o$

Since volume is constant then

$$NB_{oi} = (N - N_P)B_0$$
$$NB_{oi} = NB_o - N_pB_o$$
$$N_pB_o = NB_o - NB_{oi}$$

Therefore
$$N = \frac{N_pB_o}{B_O - B_{Oi}} \qquad (2.6)$$

Fractional recovery factor $\frac{N_P}{N} = \frac{B_O - B_{Oi}}{B_O}$

2.1.4.2 Material balance equation for volumetric saturated oil reservoir

For a volumetric Reservoir, the volume of the reservoir remains constant i.e.

$$V_{oi} = V_0 + V_g$$

where V_{oi} = volume of initial oil
V_0 = Reservoir volume of oil
V_g = Volume of gas at reservoir condition.

If the cumulative production at surface is N_P in STB, the initial volume of oil V_{oi} can be found by volumetric method. But $V_{oi} = NB_{oi} = 7758Ah\phi(1 - s_w)$. If N is the initial volume of oil in place and N_p is oil produced, at the surface, oil remaining is $(N - Np)B_0$. Therefore

$$NB_{oi} = (N - Np)\,B_o$$

If G_f is gas produced at reservoir condition, then gas produced at surface condition is $G_f \times B_g$, where B_g = *gas* formation volume factor. Therefore

$$\therefore \quad NB_{oi} = (N - N_p)B_o + G_f B_g$$

If initial *gas = solution gas + free water + produced gas*

$\therefore$ *free gas = initial gas – solution gas – produced gas.*

i.e $$G_f = NR_{si} - (N - N_p)\,R_s - N_pR_p$$

$$\therefore \quad NB_{oi} = (N - N_P)B_o + [NR_{si} - (N - N_p)R_s - N_pR_p]B_g$$

$$NB_{oi} = NB_o - N_PB_o + (B_gNR_{Si} - (NB_g - N_PB_g)R_S - N_PR_PB_g)$$

$$= NB_O - N_PB_o + B_gNR_{si} - NB_g\,R_s + N_pB_gR_s - N_pR_p\,B_g$$

$$NB_{oi} - NB_o - B_gNR_{si} + NB_gR_S = N_PB_gR_s - N_PB_o - N_PR_pB_g$$

$$N(B_{oi} - B_o - B_gR_{si} + B_gR_s) = N_P(B_gR_s - B_o - R_PB_g)$$

$$N[B_{oi} - B_o - B_g\,(R_{si} - R_s)] = N_p[B_g(R_s - R_P) - B_o]x - 1$$

$$\therefore \quad N = \frac{NP[Bo + Bg(Rp - Rs)]}{Bo - Boi + Bg(Rsi - Rs)} \tag{2.7}$$

$$\frac{Np}{N} = \frac{Bo - Boi + Bg(Rsi - Rs)}{Bo + (Rp - Rs)Bg} \tag{2.8}$$

where

B_o = oil formation volume factor
B_g = gas formation volume factor
N = Initial oil in place STB
N_p = Cumulative oil produced STB
R_s = Solution gas-oil ratio SCF/STB
R_{si} = Initial solution gas-oil ratio SCF/STB
R_p = Production gas-oil ratio SCF/STB
B_{oi} = Initial oil formation volume factor.

2.1.4.3 Generalised material-balance equation

The generalized material-balance equation often called schilthuis equation is simply a volumetric balance, which states that since the volume of a reservoir gas defined by its initial limits is a constant, the algebraic sum of the volume changes of the oil, the free gas, and the water volume in the reservoir must be zero. For example, if both the oil and gas reservoir volume decrease, the sum of these two decreases must be balanced by an increase of equal magnitude in the water volume.

If the assumption is made that complete equilibrium is attained at all time in the reservoir between the oil and its solution gas, it is possible to write a generalized material balance equation relating the quantities of oil, gas and water produced, the average reservoir pressure, the quality of water which may have encroached from the aquifer, and finally the initial oil and gas content of the reservoir.

2.1.4.4 Modification of generalised material balance equation

Recall

$$N = \frac{7758Ah\phi(1-S_w)}{B_{oi}} x \frac{N}{G}$$

where $\frac{N}{G}$ is the net/gross. But for a Reservoir that has produced for some time, the Reserve is computed thus

$$N - N_p = \frac{7758Ahr\phi(1-S_{wc})}{Bo} \times N/G \qquad (2.9)$$

But from the generalized material balance equation,

$$N = \frac{N_p\left[B_t + (R_p - R_{si})B_g\right] - (W_e - B_w W_p)}{B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})} \qquad (2.10)$$

combining equation (2.9) and (2.10) we have

$$\frac{N_p\left[B_t + (R_p - R_{si})B_g\right] - (W_e - B_w W_p)}{B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})} - N_p = \frac{7758Ahr\phi(1-S_{wc})}{B_o}$$

$$\frac{N_p\left[B_t + (R_p - R_{si})B_g\right] - (W_e - B_w W_p) - N_p\left[B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})\right]}{B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})} = \frac{7758Ahr\phi(1-S_{wc})}{B_o} \times N/G$$

$$\frac{{}^{-}B_O\left[N_P \; \left[B_t + (R_p - R_{si})B_g\right] - (W_e - B_w W_p) - N_p\left[B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})\right] = 7758Ahr\phi(1-S_{wc})\right.}{B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi}) \times N/G}$$

$$\therefore h_r = \frac{B_O\left[N_P \; \left[B_t + (R_p - R_{si})B_g\right] - (W_e - B_w W_p) - N_p\left[B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})\right]\right.}{7758\, A\phi(1-S_{wc})\left[\; B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi}) \;\right] \times N/G} \qquad (2.11)$$

where

h_r = Reservoir thickness
B_0 = oil formation volume factor
N_p = cumulative oil produced
R_p = Producing gas – oil ratio
R_{si} = initial solution gas – oil ratio
B_g = gas formation volume factor
W_e = cumulative water influx
B_w = water formation volume factor
W_P = cumulative water produced in barrels at standard condition
$B_r = [B_o + (R_{si} - R_S)B_g]$
$B_{ti} = B_{oi}$ = Initial oil formation volume factor
$M = GB_{gi} / 5.615NB_{oi}$ = ratio of initial gas – cap – gas
Reservoir volume to initial reservoir oil volume

3.0 Results

3.1. Application of material balance equation in the determination of fluid contact

In trying to determine new fluid contact from a reservoir that has produced for some time, two reservoirs A and B in Niger Delta will be used as concrete examples. Table 3.1 shows the parameters of the two reservoirs.

Table 3.1: Parameters of the two reservoirs

Parameters	***Reservoir(A)***	***Reservoir(B)***
STOIIP	78.8MMstb	9.8MMstb
N_P	14.1MMstb	4.44MMstb
R_P	429scf/stb	797scf/stb
R_{si}	320scf/stb	650scf/stb
B_{gi}	0.006146scf/stb	0.006131scf/stb
B_{oi}	1.175bbl/stb	1.346bbl/stb
Gross Res. Vol.	51.54mac-ft	8.37mac-ft
Crest of structure	5700 ftss	6080ftss
O_{owc}	582ft	615ft
Avg gross sand thickness	76ft	220ft
Porosity	0.13	0.30
Net/gross(N/G)	0.97	0.94
S_{wc}(Avg)	0.23	.24
B_w	1.02	1.02
W_e	21.53 X 10^6stb	13.90 X 10^6stb
W_p	4.10MMstb	5.17MMstb
Initial Pressure	2540psi	2690psi
Initial Temperature	167^0 f	173^0 f
Current Pressure	2280psi	264psi
Current Temperature	167^0 f	173^0 f
Bubble point Pressure	2085psi	2585psi

3.2 Computation of current oil water contact for reservoir A

Above Reservoir parameters for A and B are located in Niger delta and both Reservoir where drilled in 1972 and have produced for 30 years.

Considering Reservoir A

Initial oil in place

$$N = \frac{7758Ah\phi(I - Sw)\times N/G}{B_{oi}}$$

where, Ah = Gross Reservoir volume = 51.54×10^3 ac – ft

Table 3.2: Parameters of current oil water contact for reservoir A.

Parameters	***Reservoir(A)***
Φ	0.31
S_w	0.23
N/G	0.97
Boi	1.175bbl/stn
N	78.8MMstb

Recalling (2.11), $h_r = \dfrac{B_O [N_P \lfloor B_t + (R_p - R_{si})B_g \rfloor - (W_e - B_w W_p)}{7758 \; A\phi(1 - S_{wc})\,\mathrm{N/G}\,[\; B_t - B_{ti} + \frac{mB_{ti}}{B_{gi}}(B_g - B_{gi})\;]}$

We have

$$\therefore\; Ah_r = \frac{B_o\{N_p\lfloor B_t + (R_p - R_{SI})B_g \;\rfloor - (W_e - B_w W_p) - N_p(B_t - B_{ti})\;\}.........1.12}{7758\phi(I - Sw)(B_t - B_{ti})}$$

$$= \frac{1.175\{14.1\times10^6\lfloor 1.329 + (429 - 320)\times 0.006146\;\rfloor - (21.53\times10^6 - 1.02\times 4.1\times10^6)}{7758x0.31x0.77x(1.329 - 1.175)x0.97}$$

$$= \frac{1.175(28.18\times10^6 - 17.35\times10^6 - 2.17\times10^6)}{276.62}$$

$402.67h_r = 36785.12$

$h_r = 91.35$ft

Old Oil water contact (***O**~owc~*) = 5828*ft*

Crest of structure = 5700*ft*

∴ Oil column (*h*) = 5828 – 5700

h = 128ft

But $h_r = h - C_{owc}$ (Current oil water contact)

$91.35 = 128 - C_{owc}$

∴ $C_{owc} = 36.61$ft

Note $B_t = (B_o + (R_{si} - R_S)B_g$

1.175 +(320 – 295) × 0.006146 = 1.329*bbl/stb*

3.3 computaton of current oil water contact for reservoir B

Recall, $N = \dfrac{7758Ah\phi(I - Sw)\times N/G}{B_{oi}}$

$$N = \frac{7758\times 8.37\times10^3\times 0.3\times 0.72\times 0.94}{1.346}$$

$N = 9.8mmstb$

Recalling equation (2.11)

$$Ah_r = \frac{B_0\{N_p[B_t + (R_p - R_{si})B_g \quad] - (W_e - B_w W_p) - N_p(B_t - B_{ti}) \ \}}{7758\phi(I - Sw)(B_t - B_{ti})N / G}$$

$$\frac{1.346\{4.4\times10^6[1.524+(797-650)\times0.006131] - (13.90\times10^6 - 1.02\times5.17\times10^6) - 4.4\times10^6(1.524-1.346)]}{7758\times0.3\times0.72\times0.94(1.524-1.346)}$$

$$= \frac{1.346[10.67\times10^6 - 8.63\times10^6 - 0.78\times10^6]}{280.38}$$

$Ah_r = 6063.20 acft$

Old Oil water contact (O_{owc}) = 6150ft

Crest of structure = 6080ft

∴ Oil column (height) = 70ft

Gross rock volume (GRV) = 8.37×10^3ac-ft

∴ Area = $\frac{8.37\times10^3}{70}$ = 119.57ft2

∴ $119.57h_r = 6063.20$

$h_r = 50.59$ft.

but $hr = h$ – current oil water contact (C_{owc})

∴ $50.71 = 70 - C_{owc}$

∴ $C_{owc} = 70 - 50.59 = 19.29$Ft

4.0 Analysis of result obtained from this method

4.1 Material balance equation method

The generalized material-balance equation is simply a volumetric balance, which equates total production balance to the difference between the initial volume of hydrocarbons in the reservoir to the current volume [1].

A direct application of material balance in the determination of current oil water contact will not be possible because in the equation, reservoir thickness is not included. To do this, the material balance has to be equated in with the volumetric method of computing the oil in place.

The result of this gives the modified material balance equation (2.11) which was applied to determine the current oil water contact (C_{OWC}). For reservoir A, the C_{OWC} is 36.61ft and for reservoir B the (C_{OWC}) is 19.29ft.

4.2 Comparison between M.B.E carbon oxygen methods

In the derivation and application of the modified material-balance equation, the following assumptions were made

- There is a clear sweep of oil from the reservoir to the surface
- Uniform displacement of fluid in the reservoir.
- Constant wettability

An extensive sensitivity analysis of the numerical simulation to predict the current Oil water contact, and result compared with well log reveal a sensitive results. For reservoir A, the difference between both methods in the position of C_{OWC} is 2ft while that of reservoir B os 0.7ft. This is an indication that both results were consistent for the reservoir understudy. It is important to note that one of the most important parameter needed in the computation of C_{OWC} is the water influx and the value must be properly estimated.

5.0 Conclusion

The results obtained from the comparison of the Carbon /oxygen logging method and the Material Balance Equation(M.B.E.) method show that the percentage error is very minimal. Therefore since the results are similar, the accuracy is established. However, the M.B.E. is by far more economical, faster and therefore affordable by small scale oil and gas industries especially in the acquisition of marginal oil and gas field.

The material balance method may be applied not only to evaluate the original-hydrocarbons-in-place, but also to evaluate the remaining reserves. Better understanding of these reserves is essential for studying production.

The application of the material balance depends largely on the reservoir parameters and the accuracy of measurement is also very important. Some of the parameters that may hinder the application include but not limited to:

(1) Cumulative water production
(2) Water influx
(3) Initial solution gas oil ratio
(4) Producing gas oil ratio
(5) Total oil formation volume factor.

It is recommended that when all relevant parameters are available, material balance equation should be applied to serve as a check for current oil water contact obtained with logging data.

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