IJEW 国际工程期刊 International Journal of Engineering Works انجینرنگ کاموں کا بین الاقوامی جرنل

International Journal of Engineering Works
ISSN-p: 2521-2419
ISSN-e: 2409-2770
Vol. 5, Issue 9, PP. 124-129, September 2018
https://www.ijew.io/

Waterflooding: A key Option for Stratified Oil Reservoirs in the Niger Delta

Patrick Godwin Oyindobra Ossai[1] , Princewill Nnaemeka Ohia[2]
Department of Petroleum Engineering, Federal University of Technology, Owerri, Imo State, Nigeria[1,2]
engrpatrickossai@yahoo.com[1], princepetra@yahoo.com[2]
Received: 02 July, Revised: 10 August, Accepted: 28 August

***Abstract*—**This research work looked at the applicability concept of waterflooding as a key option for enhanced recovery of oil from stratified reservoirs in the Niger Delta, South of Nigeria. Waterflooding is a secondary recovery technique that commences after a homogeneous or multi-layered (stratified) reservoir has reached its economic limit by every possible primary recovery drives (i.e. natural drive mechanisms). The research also covered for Niger Delta the sweep/displacement efficiency deliverability of multi-layered (stratified) reservoirs, reservoir permeability ordering, the effect of waterflooding rates, and effectiveness of waterflooding schemes for multi-layered oil reservoirs, fractional flow of water during waterflooding processes, and the frontal advancement of the water front along the reservoir bed at a given time (t) in days.

***Keywords*—**Stratified reservoir, Multi-layered reservoir, Sweep Efficiency, Displacement Efficiency, Niger Delta, Buckley-Leverette theory, Waterflooding, Water Injection, Enhanced Oil Recovery

I. Introduction

It is already a known fact that waterflooding is one of the most cost effective and efficient secondary oil recovery technique for mostly offshore oil reservoirs worldwide. Every oil reservoir producing using its natural drive mechanisms must definitely reach its economic limit in no distance time. Hence, there is the need for a secondary recovery technique such as waterflooding. Reservoirs are known to be homogeneous (less complex system) or multi-layered/stratified (complex to very complex reservoir systems). These complex reservoirs that are multi-layered or stratified usually have varying reservoir characteristics horizontally or vertically or both (as the case may be). The important effects of waterflooding as a secondary oil recovery technique are demanding increasing attention in technical enhanced oil recovery (EOR) literatures worldwide. We have two distinguished cases of waterflooding in stratified oil reservoirs. They are:

1. Waterflooding in a stratified reservoir with cross-flow: This means that there is communication between the multi-layers of the oil reservoir
2. Waterflooding in a stratified reservoir without cross-flow: This also means that there is no communication between the multi-layers of the oil reservoir (probably as a result of isolation)

For the first category (with cross-flow), the stratified or multi-layered reservoir is assumed to consist of discrete layers that are uniform (homogeneous) within itself. Only differing from each other in properties such as:

a. Absolute permeability (k)
b. Thickness (h) and
c. Porosity

The performance within each individual layers can be calculated by one dimensional flow theory. The performance of the total stratified reservoir can be gotten by adding up the individual layer performances. It is also expedient to note here also that the capillary and gravity effects are negligible. As for the second category (without cross-flow), things are more relatively complex and difficult since there are capillary and gravity effects that plays a vital role which cannot be neglected. Gravity and capillary effects are responsible for the cross-flow (communication) between layers except in cases of isolation. The differential equations which rigorously describe waterflooding in stratified or multi-layered reservoirs are usually non-linear. Hence, does not facilitate analytical solutions to problems. But, by applying the finite difference approximations one can possibly derive solutions to any degree of accuracy. ADIP (Alternating Direction Implicit Procedure) is one such solution provided by computers. ADIP explores systematically the effects of very important parameters used in waterflooding performance of two-dimensional, two-layered, field scale model of water-wet stratified sandstone reservoir.

II. PREDICTING WATERFLOODING BEHAVIOUS IN A STRATIFIED RESERVOIR

Predicting waterflooding behavior is very possible using an already existing flexible model that can approximate the cross-flow effects during the process. This model depends on slight changes in the Dietz's theory which create room for adjusting both the permeability and hydrocarbon pore volume. It is also very possible to assume in few cases that the permeability can be characterized by a log-normal distribution. Whereas the hydrocarbons pore volume is characterized by normal distribution. A simple graphical method can help a field engineer to predict the behavior of a stratified waterflooding process. In comparison to other methods we can conclude that:

1. The effects of variations in hydrocarbon pore volume can be neglected under normal conditions.
2. Cross-flow (communication) effects in a stratified/multi-layered reservoir system can be appreciable if the mobility ratios (M) are favorable or unfavorable.
3. Failure to utilize all available permeability data can lead to large avoidable errors when predicting waterflooding behavior for a stratified reservoir.

a. The Effects Of Waterflooding Rate And Permeability Ordering In A Stratified Redservoir

The waterflooding performance of a highly stratified reservoir in which the layers are systematically arranged can be greatly affected by gravity segregation that will also depend on the flooding rate and permeability ordering. Cross-flow is also affected by capillary and gravitational forces to a large degree by flooding rate and permeability ordering in multi-layered reservoir.

Two cases of systematic permeability ordering can be considered as thus:

i. Layers can be arranged in an ordering form starting from the most permeable layer to the least permeable one. The most permeable strata is considered to be at the top.

ii. Here layers are arranged in the opposite manner with the least permeable layer/strata is considered to be at the top.

Most importantly, it must be noted that stratified reservoirs can be in any random permeability ordering.

b. Predicting Waterflooding Performance In A Stratified Reservoir Systems

The analytical solutions detailing the cross-flow effects are very possible but only under limiting conditions. These limiting conditions are:

a. Where vertical equilibrium exist as a result of gravity and capillary displacement dominance.

b. Where there are highly viscous forces in dominance resulting to no cross-flow.

In most cases a less expensive two-dimensional area x-y model can be employed to solve engineering problems adequately provided the non-uniform distribution of fluid flow in the third or vertical dimension of the areal model is adequately described. Invariably, this implies also that the input data must be varied with respect to the two-dimensional area so that it can account for the vertical effects.

c. Predicting Waterflooding Performance By The Graphical Representation Of Porosity And Permeability Distribution In Stratified Reservoirs

One simple tool that is now available for prediction waterflooding performance from stratified reservoirs has been developed using variations of familiar layer concept. These variations allows for consideration of non-uniform porosity, development and mobility ratio. Such procedure considers predicting cumulative water injected and also the cumulative oil production based on percent water-cut using porosity-permeability system classification. The ease of utilizing the graphical approach to the cumulative oil recovery against the water-cut prediction makes it much easier to evaluate the areal plus the vertical aspect of the flood performance. Most procedures are common to other methods except for the following:

1. It is unnecessary to assume uniform porosity distribution and uniform water saturations
2. It was assumed that in layers of equal permeability capacity, advancement of the water front is not proportional to the mobility of hydrocarbon volume of the layer.
3. Changing the mobility ratio during fill-up periods was assumed.

To evaluate the effect of stratification on vertical sweep efficiency the reservoir permeability data from core analysis must classified based on systems similar to what was proposed by law.

d. Waterflooding Performance Of Communicating Stratified Reervoir With A Log-Normal Permeability Distribution

Analytical answers can be gotten for waterflooding performance of stratified reservoirs with log-normal permeability distribution provided the possibilities of cross-flow exist. The characteristic of the permeability distribution is given by Dykstra-persons variation coefficient which is related to the standard deviation of the log-normal distribution. Its performance is represented as vertical converge as a function of the producing water-oil ratio (WOR). An analogy to the Buckley-Leverette multiple value saturation is found to occur in the law of mobility ratio ($M<1$) where a multiple valued displacement front is formed. The log-normal permeability is characterized by two permeates and they are:

a. The standard deviation and
b. The mean permeability

e. Combination Method For Predicting Waterflooding Performance In Stratified Reservoir

A solution that predict waterflooding performance has been created and it combines certain aspects of other published techniques. This approach is based on computer solutions and has eliminated the need for consulting plotted curves. Invariably, it allows for analytical prediction of waterflooding performance for a stratified reservoir. Values predicted are measured in common oil field units rather than in dimensionless terms. The whole calculation process has been programmed into FORTRAN IV and is readily available to users.

f. Waterflooding Performance Of Stratified Reservoir Systems

Most published analytical methods as at today that is utilized for the prediction of waterflooding performance of stratified reservoirs does not take into account the actual spatial position of the layers in the reservoir. They commonly assumed a position of layers without existing cross-flow between the strata. Today, further reservoir engineering research has revealed that wide variations of reservoir properties like porosity, permeability, and capillary pressures exist within the individual units in the stratified system.

g. The Effectiveness Of Waterflooding Scheme For A Multi-Layered Reservoir

Waterflooding scheme effectiveness for multi-layered reservoirs depends on the following:

i. The areal extent
ii. The vertical sweep efficiency and
iii. The microscopic displacement

These factors are determined by detailed reservoir studies. But, a quick assessment of a waterflooding scheme performance can be done by assigning values (0.0-0.1) for each factor listed above. The overall waterflooding efficiency can be computed by multiplying these three values. For instance, a stratified reservoir that has areal, microscopic and vertical sweep efficiency of 0.5, 0.6 and 0.7 would have an overall waterflooding efficiency of 0.21. This means that only 21% of the oil in place can be recovered using the scheme. Both areal and vertical sweep efficiency depends on large variety of factors. Such as:

1. Perforation placement
2. Well spacing
3. Injection/production rates
4. Reservoir thickness
5. Reservoir fluid properties/characteristics
6. Wettability
7. Anisotropy
8. Distribution of both horizontal and vertical permeability
9. Type of injected fluid (water or gas)

III. Inroducing the Study Model/theory

The Buckley-Leverette theory/model uses two distinctive equations, namely:

IV. The frontal advancement equation and
V. The fractional flow equation

Buckley-Leverette (B-L) made the following theoretically assumptions:

a. The displacement is incompressible (steady state)
b. The displacement takes place via vertical equilibrium
c. Water is displacing oil in a water-wet reservoir
d. The displacement is considered linear

The generalized fractional flow equation proposed by Buckley-Leverette is given as:

$$F_W = \frac{1-\left(\frac{dPc}{dx}+g\Delta\rho Sin\theta\right)\frac{ko}{q_t \cdot \mu_o}}{1+\frac{k_o}{k_w} X \frac{\mu_w}{\mu_o}} \tag{1}$$

In field or practical units, the fractional flow equation proposed by B-L becomes:

$$F_W = \frac{1-\frac{1.127\, ko}{q_t \cdot \mu_o}(g\Delta\rho Sin\theta + \frac{dPc}{dx}}{1+\frac{ko}{kw} X \frac{\mu_w}{\mu_o}} \tag{2}$$

Note:
If we neglect capillary effect and consider the reservoir to be horizontal, then the fractional flow equation is given as:

$$F_W = \frac{1}{1+\frac{ko}{kw} X \frac{\mu_w}{\mu_o}} \tag{3}$$

Now, expressing fractional flow equation in terms of reservoir volumes we have:

$$F_W = \frac{1}{1+(\frac{Ko}{Kw} X \frac{Bw}{Bo} X \frac{\mu w}{\mu o}} \tag{4}$$

Since (Ko/Kw) is a function of saturation, then equation (4) above becomes:

$$F_W = \frac{1}{1+(ae^{-bSw} X \frac{Bw}{Bo} X \frac{\mu w}{\mu o}} \tag{5}$$

On the hand, the frontal advance equation proposed by B-L theory is represented as:

$$\text{Frontal Advance, } X = \frac{q\, X\, t}{A\emptyset}(DF_W/DS_W) \tag{6}$$

The above equation (6) is valid provided (q) unit is in bbl/day

$$\text{Frontal Advance, } X = \frac{5.615\, q\, X\, t}{A\, \emptyset}(DF_W/DS_W) \tag{7}$$

Equation (7) is only valid if (q) unit is in cuft/day

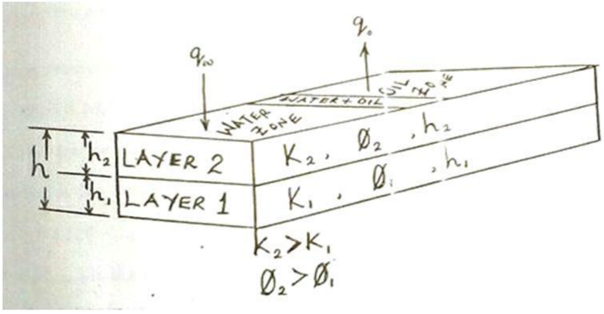

Fig. 1: Displacement in a Non-homogeneous reservoir model

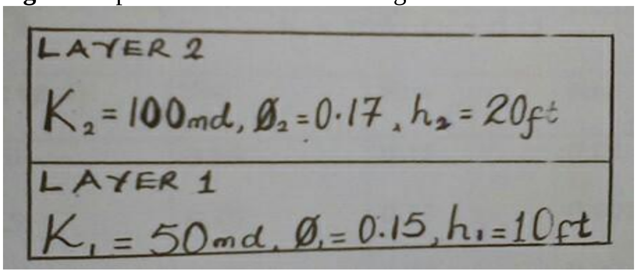

Fig. 2: Reservoir parameters of the Niger Delta stratified reservoir

Note:
The angle of inclination of the Niger Delta stratified reservoir is zero (i.e. $\theta = 0$), water viscosity, μ_w= 0.5cp, oil viscosity, μ_o= 5cp, specific gravity of the oil, γ_o=0.81 and specific gravity of the water, γ_w=1.04

Now, capillary pressure is related to capillary rise by:

$$DP_C = 0.1DZ \text{ (PSI)} \quad (8)$$

The phase pressure difference at the center of the reservoir is given by:

$$P_C|_0 = 0.1\,(20 - Z_{1\text{-}SOR}) \quad (9)$$

Where:
$Z_{1\text{-}Sor}$ = Elevation of maximum water saturation and
Sw = 1 – Sor

Mathematically, we have:

1. The average water saturation for the Niger Delta stratified reservoir Layer 1 is given as:

$$\Sigma \overline{S_{w1}} = \Sigma \frac{Sw\ X\ Z_1^2}{h_1} \quad (10)$$

2. The average water saturation for the Niger Delta stratified reservoir Layer 2 is given by:

$$\Sigma \overline{S_{w2}} = \Sigma \frac{Sw\ X\ Z_2^2}{h_2} \quad (11)$$

3. The average water saturation of the Niger Delta stratified reservoir is given as:

$$\overline{S_w} = \frac{h1Ø1\Sigma Sw\ 1 + H2Ø2\Sigma Sw\ 2}{h1Ø1 + h2Ø2} \quad (12)$$

4. $K_{RW}(\ \overline{S_w}\ ) = \frac{\int_0^h K(Z)Krw(Sw(Z))dZ}{\int_0^h K(Z)dZ} = \frac{h1K1Krw\,1(Sw1) + h2K2Krw\,2(Sw2)}{\sum h_j k_j \quad (j=1)}$ (13)

5. $K_{rw1}S_{w1} = \frac{\int_0^{h1} Krw(Sw(Z))dZ}{h1}$ (14)

6. $K_{rw2}S_{w2} = \frac{\int_0^{h2} Krw(Sw(Z))dZ}{h2}$ (15)

3.15 *Niger Delta Stratified Reservoir Data And Results In Summary*

Table 1: Stratification data and Calculated Results for Niger Delta Reservoir Layer 1

STRATIFICATION LAYER 1: h_1 = 10ft, Ø = 0.15					
Z (ft)	Pc (psi)	Sw (%)	Krw (mD)	Kro (mD)	$\overline{S_{w1}}$ (%)
10	1.0	0.69	0.18	0.020	3.45
5	0.5	0.78	0.23	0.002	3.90
0	0.0	0.80	0.24	0.000	4.00
					$\sum \overline{S_{w1}}$ = 11.35 %

Table 2: Stratification data and Calculated Results for Niger Delta Reservoir Layer 2

STRATIFICATION LAYER 1: h_2 = 20ft, Ø = 0.17					
Z (ft)	Pc (psi)	Sw (%)	Krw (mD)	Kro (mD)	$\overline{S_{w2}}$ (%)
30	3.0	0.22	0.001	0.55	2.20
25	2.5	0.24	0.003	0.50	2.40
20	2.0	0.29	0.020	0.40	2.90
15	1.5	0.45	0.070	0.18	4.50
10	1.0	0.63	0.170	0.05	6.30
					$\sum \overline{S_{w2}}$ = 18.3%

From the stratification data Table 1 & 2 and applying equation (12), the average water saturation for the Niger Delta stratified reservoir is given as:

$$\overline{S_w} = \frac{h1\emptyset1\Sigma Sw1 + h2\emptyset2\Sigma Sw2}{h1\emptyset1 + h2\emptyset2}$$

$$\overline{S_w} = \frac{(10\ X\ 0.15\ X\ 11.35) + (20\ X\ 0.17\ X\ 18.3)}{(10\ X\ 0.15) + (20\ X\ 0.17)} = \frac{(17.025 + 62.22)}{(1.5 + 3.4)}$$

$$= \frac{79.245}{4.9} = 16.2\%$$

Sweep Efficiency Consideration For The Niger Delta Stratified Reservoir

Sweep efficiency is the ratio of the volume swept at any given time against the total volume subjected to invasion. Sweep efficiency can be expressed as:

i. Pattern Efficiency
ii. Volumetric Efficiency and
iii. Invasion Efficiency

For a single linear homogeneous reservoir or bed, we have that:

RECOVERY = SWEEP EFFICIENCY (S.E) X DISPLACEMENT EFFICIENCY (D.E)

But, for a stratified or multi-layered reservoir like that of this Niger Delta oil reservoir, we have it as:

RECOVERY = SWEEP EFFICIENCY (S.E) X DISPLACEMENT EFFICIENCY (D.E) X CONFORMANCE

Sweep Efficiency Calculations For The Niger Delta Stratified Reservoir Considering A 5-Spot Pattern

Table 3: Reservoir data / stratification parameters

Reservoir Parameters	Values
Relative water permeability, (Krw)	0.24
Relative oil permeability, (Kro)	0.80
Oil viscosity, (μ_o) cp	5.00
Water viscosity, (μ_w) cp	0.50
Oil formation volume factor, (Bo)	1.31
Initial oil saturation, (Soi)	0.65
Residual oil saturation, (Sor)	0.30
Reservoir porosity, (∅) %	0.20
Reservoir area, (A) sq.ft	10.00
Reservoir pay thickness, (H) ft	30.00
Layer 1 thickness, (h_1) ft	10.00
Layer 2 thickness, (h_2) ft	20.00
Specific oil gravity, (γ_o)	0.81
Specific gravity of water, (γ_w)	1.04

Mathematically:

$$\text{MOBILITY RATION, M} = \frac{Z_w}{Z_o} = \frac{K_{rw}/\mu_w}{K_{ro}/\mu_o} = \frac{0.24/0.5}{0.8/5} = 3.0$$

Taking the reciprocal of the mobility ratio we have:

$$\frac{1}{M} = \frac{1}{3} = 0.33$$

From the sweep efficiency curves/charts, 1/M = 0.33 which corresponded to a Sweep Efficiency of 54% at the initial breakthrough. This means that the recoverable oil from the Niger Delta stratified reservoir is only 54%.

$$\text{DISPLACED OIL VOLUME} = 7758 \text{ X A X H X } \emptyset(S_{oi} - S_{or}) \quad (16)$$

= 7758 x 10 x 30 (0.65 – 0.3)
= 814,590 bbls

The recovery at surface conditions is given by:

$$\text{RECOVERY} = \frac{7758\, Ah\emptyset(S_{oi} - S_{or})}{B_o} \quad (17)$$

Hence, if displacement efficiency (D.E) = 1 and sweep efficiency (S.E) = 54%

then:

$$\text{Recovery} = \frac{814{,}590\ X\ 0.54}{1.31} = 335{,}785 \text{ STB}$$

But, if displacement efficiency (D.E) = 68% and sweep efficiency (S.E) = 54%,

then:

$$\text{Recovery} = \frac{814{,}590\ X\ 0.54\ X\ 0.68}{1.31} = 228{,}334 \text{ STB}$$

CONCLUSION /RECOMMENDATIONS

A good waterflooding process has a mobility ratio that is equal to one (M = 1). But, if the stratified oil reservoir is much viscous then the mobility ratio could be greater than one (M > 1). The displacing fluid (water) sweeps faster in more permeable zones. This means that oil in less permeable zones will be produced over a longer a long period of time. A more favorable displacement (immiscible displacement) for stratified reservoirs occurs when higher permeable layers are uppermost in the reservoir. And for viscous oil having mobility ratio greater than one the displacement water will finger through the reservoir resulting to it bypassing some of the needed oil. Water is usually more efficient than gas in displacing oil from reservoir rocks. This is because the viscosity of water is almost fifty (50) times that of gas. Water is also known to occupy the less conducive portions of the pore spaces whereas gas occupies the more conducive portions. Since there are two sets of relative permeability curves there are also discontinuities in the relative permeability distributions to oil and water at the layers boundaries. The rates of advancement in the separate strata/layers will be proportional to their permeability and the overall effect will be a combination of several separate displacements such as described for a single homogeneous stratum. For best results detailed reservoir studies must be carried out before the implementation of a waterflooding scheme.

REFERENCES

[1] Ezeddin S., Gary Z. Waterflooding performance of stratified reservoirs with bottom-water conditions, SPE 77965-MS

[2] Haq S.,Reis J.C. Predicting capillary cross-flow in layered reservoirs, SPE 26651-MS

[3] James A.Wasson. Combination method for predicting waterflooding performance for 5-spot patterns in a stratified reservoir, SPE-2004, pp1195-1203

[4] Noaman A.F. El-khatib. The application of Buckley-Leverette Displacement in non-communicating stratified RESERVOIRS, SPE 68976-MS

[5] Roper W.A, Brown A., Teasdale T.S. Production performance of displacement processes in stratified reservoirs, SPE 194-MS

[6] Silva L.F, Farouq .A. Waterflooding performance in the presence of stratification, SPE 3556-MS

[7] Telleria M.S, Vriues C.J.J. Limitations in the use of the frontal advance theory for 2-Dimensional systems, SPE 54004

Patrick Godwin Oyindobra Ossai, is currently a post-graduate student at the Post Graduate School of Federal University of Technology Owerri located in Imo State, Nigeria. He holds a bachelors and masters of engineering degree (B.Eng, M.Eng) in Petroleum Engineering from the University of Benin and Federal University of Technology Owerri respectively. He has to his credit a few seasoned international journal publications in enhanced heavy oil recovery, in-situ combustion applicability, Drilling optimization and well design. Patrick is also a seasoned oil logistics and QHSE expert with NEBOSH certifications. His field expertises are in the areas of Petroleum Engineering (EOR), Oil & Gas logistics and QHSE. He is happily married with kids.

Ohia Nnaemeka Princewill, is a Senior Lecturer/Instructor with the Department of Petroleum Engineering, Federal University of Technology, Owerri. After spending over two decades teaching and consulting for both local & international oil and gas companies working on multimillion dollar projects, Nnaemeka knows what truly drives performance, which is how well you connect with the people you're trying to help and communicate your understanding back to them. Nnaemeka's research interests in environmental protection, well engineering and production optimization has landed him with various certifications and awards around the world, including over 45 authored and co-authored journal publications to his credit. Today, Ohia is a member of notable professional bodies such as Council for Registered Engineers of Nigeria (COREN), Nigerian Society of Engineers (NSE) and Society of Petroleum Engineers. In addition to his extensive research, teaching and consulting experience, Nnaemeka is a trained technical coach. Nnaemeka holds a PhD in Petroleum Engineering from the Federal University of Technology, Owerri. (FUTO), Nigeria since 2012.