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Anietie N. Okon, Dulu Appah & Julius U. Akpabio

University of Uyo

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ABSTRACT

In the Niger Delta, most of the thin oil rim reservoirs accumulate potential recoverable reserves. However, their development/ production is characterize by early water breakthrough from water coning phenomenon. Available water coning control methods reduce the water coning tendency but leave the bypassed oil in the reservoir(s). In this study, integrated water coning control approach that combines Downhole Water Loop (DWL) completion and polymeric gel injection was developed to minimize water coning tendency and improve reservoir sweep efficiency in thin oil rim reservoir(s). The simulation results obtained indicated that the integrated water coning control approach reduced water production by 62.80% and 83.26% at 6 and 3 months polymeric gel injection intervals respectively. Also, it improved oil production by 171.25% and 239.06% for the respective polymeric gel injections. Comparing the integrated approach with the DWL completion showed that the developed integrated approach performed better than the DWL completion; as the DWL reduced water production by 38.0% and improved oil production by 75.0%. Therefore, the developed integrated water coning control approach can be used as a veritable tool for minimizing water coning tendency to improve oil recovery from thin oil rim reservoirs in the Niger Delta.

Keywords: water coning, integrated water coning control approach, downhole water loop, thin oil rim reservoir, Niger Delta.

Author α ρ: Department of Chemical and Petroleum Engineering, University of Uyo, Nigeria.

σ: Department of Gas Engineering, University of Port Harcourt, Nigeria.

I. INTRODUCTION

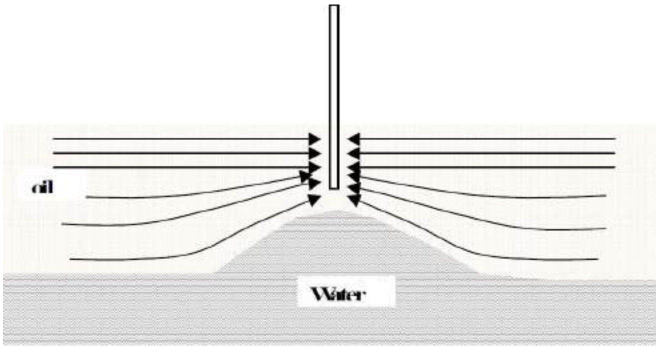
In oil and gas production, one major recurrent problem is the production of water. According to Okon and Appah (2018) the produced water in most cases is a result of the normal rise of oil water contact, water coning, water fingering, water channeling or a combination of these. In thin oil rim reservoirs, water coning is more pronounced due to its thinly oil spread column. The occurrence of this phenomenon pose serious production challenges, which includes: water handling problem at the surface, low hydrocarbon recovery, economic and environmental problems (Mahgoup and Khair, 2015; Okon *et al.*, 2018). Therefore, appropriate development and production strategies are put in place to handle this recurrent production-rate-related problem, that is, water coning. Early studies on this phenomenon focused on developing prediction correlations, namely: critical oil rate, breakthrough time and post-water breakthrough performance. These developed correlations for both vertical and horizontal wells include: Chaperon (1986), Joshi (1988), Yang and Wattenbarger (1991), Recham *et al.* (2000) whose research developed correlations for critical rate in horizontal wells. Papatzacos *et al.* (1989), Ozkan and Raghavan, (1990), Bahadori, (2010) and Makinde *et al.* (2011) developed correlations for breakthrough time in horizontal wells. On the other hand, Muskat and Wyckoff (1935), Meyer and Garder (1954), Chierici *et al.* (1964), Wheatley (1985), Chaperon (1986), Abbas and Bass (1988), Hoyland *et al.* (1989), Guo and Lee (1992), among others, presented critical rate correlations for vertical wells. Sobocinki and

Cornelius (1965), Bournazel and Jeanson (1971), Recham *et al.* (2000) and others, developed correlations for breakthrough time. While Kuo and DesBrisay (1983), Yang and Watterbarger (1991), Zamonsky *et al.* (2005) presented correlations to account for post-water breakthrough performance in vertical wells. Osisanya *et al.* (2000) reported that among these correlations, critical oil rate is the most discussed coning parameter. Okon *et al.* (2017a) maintained that these correlations only predict the coning phenomenon, which in some cases can be used to delay its occurrence. However, the correlations cannot totally attenuate the water coning tendency to its barest minimum. On the other hand, numerous water coning control methods have been developed, these include: conformance technology, horizontal well technology, downhole oil-water separation technology, intelligent well technology, etc. Interestingly, some of these technologies have successful field application as reported in the literature (Okon *et al.,* 2017a).

The Niger Delta like other regions in the world has several thin oil rim reservoirs with potential recoverable reserves. Literatures on some Niger Delta oil reservoirs indicated that most of them have less than 80 feet thick oil columns and are therefore vulnerable to coning problem (Kabir *et al.*, 2004; Mogbo, 2010). One important issue in the development of these reservoirs is water and/or gas coning problems that have detrimental effects on the ultimate oil recovery and the project economics (Okon, 2018). Onwukwe *et al.* (2012) reported that due to high coning occurrences in the Niger Delta, most wells have been shut-in and recompleted in order to combat this problem. As earlier mentioned, there are several developed water coning control methods, however, these methods have a major drawback – they leave bypassed oil in the reservoir (Okon *et al.*, 2017b). For thin oil rim reservoirs in the Niger Delta, there is no established approach for minimizing water production due to water coning. Therefore, it is pertinent to study water coning phenomenon in thin oil rim reservoirs in the Niger Delta to develop integrated approach to minimize water coning and produce the bypassed oil in the reservoir using an integrated reservoir model.

1.1 Water Coning Development in Reservoirs

Before the development and production of oil and gas, the oil-water contact is supposedly flat, stable and practically distant away from the wellbore perforations (Permadi and Jayadi, 2010). Therefore, the forces acting on the interface of the oil-water contact are at equilibrium. During oil production, the steady-state flow condition is prevalent as flow rate and pressure at the outer boundaries are constant which in turn leads to a constant pressure drawdown at every point within the reservoir boundaries (Tabatabaei *et al.,* 2012). Thus, there is a dynamic flow of oil towards the perforated interval aided by the break in equilibrium between the viscous forces and gravitational force. This imbalance in equilibrium between these forces favours the viscous force which leads to a sharp increase in flow rate and ultimately forming a cone-like shape (Tabatabaei *et al.,* 2012). Therefore, an increase in production rate initiates an increase in the height of the cone as it moves towards instability and results in water breakthrough. This instability of the cone is as a result of the strong upward dynamic force caused by high pressure drawdown which cannot be equaled by the weight of water. Tabatabaei *et al.* (2012) alluded that water breakthrough occurs at a point above which the dynamic pressure gradient is greater than the hydrostatic pressure gradient. Thus, Figure 1 depicts the schematic of water coning in vertical well.



Source: Inikori (2002)

Figure 1: Schematic representation water coning in vertical wells

1.2 Water Coning Control Methods

In the petroleum industry, several authors had developed methods to control water coning in bottom-water drive reservoirs. These methods include: selective water plugging (Kisman, 1991); chemical gelled baffles (Paul and Strom, 1988); optimized perforations (Ehlig-Economides *et al.*, 1996); horizontal wells (Joshi, 1991; Chen, 1993; Permadi, 1997); producing oil and water separately with downhole water sink (DWS) or downhole water loop (DWL) (Wojtanowicz *et al.*, 1991; Siemek and Stopa, 2002), among others. In addition, Tu *et al.* (2007) identified some of these methods as key production techniques used to control water coning during early production of oil and gas. However, these water coning control methods have their limitations on the bottom-water drive reservoirs or/and the wellbore vicinity. The comparison of some water coning controls methods were reported by Okon *et al.* (2017b) as presented in Table 1.

Table 1: Comparison of some water coning control methods.

	Control Methods	Completion	Advantage(s)	Limitation(s)	Candidate Reservoir
i.	Conformance technology	Injecting polymers or gels to form a barrier between oil and water zones.	Delayed breakthrough time and reduce water cut.	The polymers or gels may plug the reservoir pore connectivity which can impaired fluid flow The well may damage when the polymer or gel barrier enters the oil completion.	Both water-drive reservoirs with inactive and active aquifer.
ii.	Horizontal wells	Drill horizontal well into the oil zone.	Compared to vertical well in the same oil zone, it provides delayed breakthrough time and high oil recovery potentials.	Horizontal wells are constrained by drilling technology. It is expensive than its conventional counterpart.	Conventional and thin-oil column reservoirs with both weak and active aquifer.
iii.	Downhole oil-water separation technology	Well completed with installed hydrocyclone and pumps to separate water from oil mixture.	Production of water free oil at the surface, reduce water handling at the surface, etc.	Hindered the minimum casing size requirement.	Conventional and thin-oil column reservoirs with both weak and active aquifer are candidate.
iv.	Downhole water sink (DWS)	Dual completion; above and below the oil-water contact (OWC)	Increase critical rate and low water cut. Delayed or breakthrough time	Production of water and handling problems. More energy consumption and high lifting cost Completion of dual zone is expensive than conventional (single) well	Conventional reservoir with large active aquifer

v.	Downhole water loop (DWL)	Triple completion; one above oil-water contact and two below OWC (i.e., one completion at DI and other at DWI).	Increase critical rate and low water cut, with delayed breakthrough time; Better performance at reservoir pressure maintenance; No production and handling of water at the surface, Less energy and consumption cost of water pump.	Due to complexity and water coning dynamic, it requires careful design of the production system; Limited by the thickness of the aquifer; Completion of three intervals is expensive.	Weak (inactive) bottom-water drive reservoirs
vi.	Thin-horizontal downhole water loop (THDWL)	Quadruple (four) completion; one above OWC for production of oil and three below OWC.	Handling the drawback observed in the DWS and DWL. Less or low water cut than DWS and DWL.	Very expensive than DWS and DWL completion approach.	Both water drive reservoir with weak and active aquifer.
vii.	Intelligent or smart completions	Well completed with installed inflow control valves (ICVs), sensors, gauges, etc.	Monitor, regulate and measure reservoir and fluid parameters. Increase reservoir productivity.	Very expensive due to high cost of installed ICVs, etc. Reliability of the downhole valves and sensor are considerable factors for monitoring and control.	Conventional and thin oil column reservoirs with high recoverable reserves are possible candidate.

Source: Okon et al. (2017b)

II. INTEGRATED WATER CONING CONTROL APPROACH DEVELOPMENT

The developed integrated water coning control approach for thin oil rim reservoir in this study was based on the works of Smith and Pirson (1963), Hoyt (1974) and Paul and Strom (1988) combined with Downhole Water Loop (DWL) technology. Smith and Pirson (1963) and Hoyt (1974) suggested injection of some of the produced oil into the formation below the production intervals to build pressure gradient barriers and in so doing suppress water coning. Also, Paul and Strom (1988) proposed injection of water–soluble polymeric gel to control bottom water mobility. Thus, the schematic of the developed integrated water coning control approach as used in the reservoir models (Figures 3) is depicted in Figure 2. The integrated water coning control approach involved the use of producer and injector wells. The producer well was completed based on DWL configuration, with one oil production interval at the oil zone and two completions, that is, water drainage interval (WDI) and water re-injection interval (WRI) at the water zone (aquifer). On the other hand, the injector well had two completions; one completed near the water-oil contact (WOC) and the other at the mid depth between WDI and WRI (Figure 2). The integrated water coning control approach was simulated using the reservoir model depicted in Figure 3. The polymeric gel injection in the injector well was activated with the keyword "POLYMER" at the RUNSPEC and WELLSPEC sections in the Eclipse-100 input data file. The completion intervals and depths of the wells: producer and injector are presented in Table 2. These intervals in the producer well with DWL completion are presented in Figure 4.

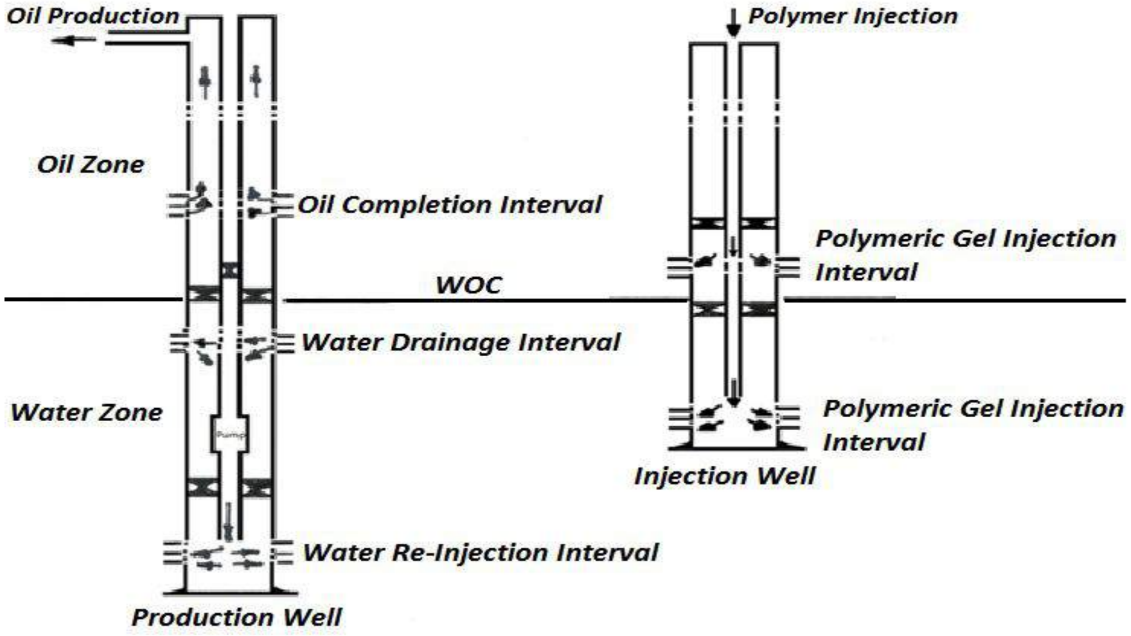


Figure 2: Well configuration of the developed integrated water coning control approach.

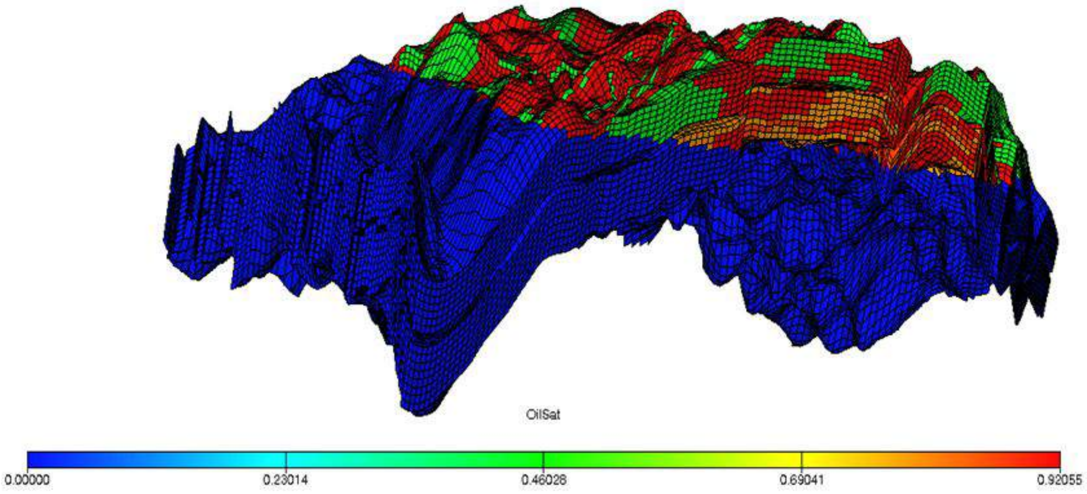
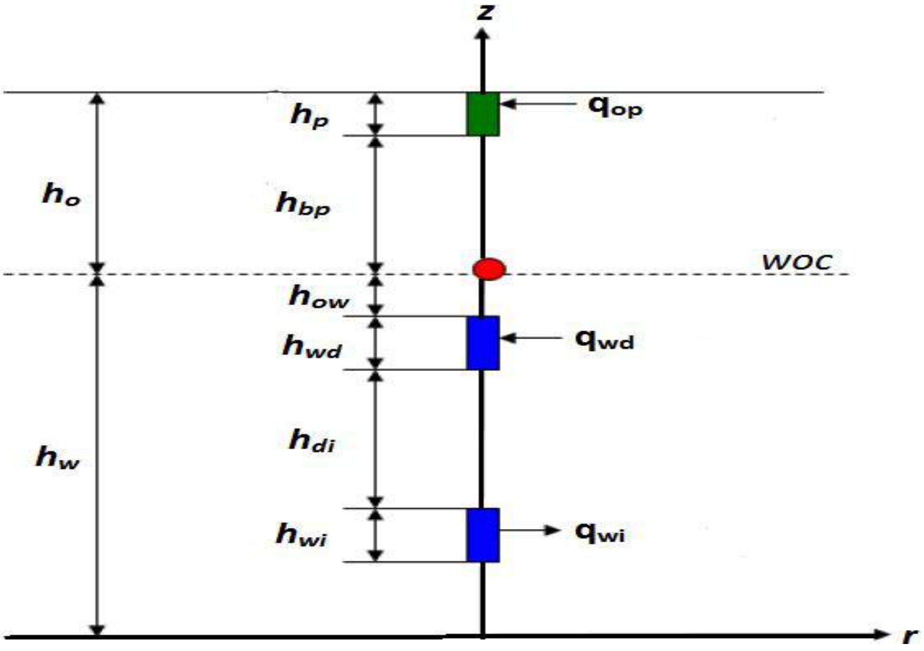


Figure 3: Reservoir model of the thin oil rim reservoir in the Niger Delta

Table 2: Description of producer and injector wells completion intervals

	Producer Well	Depth	Injector Well	Depth
i.	completion interval above WOC (h_{bp}), ft	60	injection interval depth above WOC, ft	5
ii.	depth above completion interval (h_{ap}), ft	10	polymer injection interval depth below WOC, ft	23
iii.	completion interval (h_p), ft	10	polymeric gel injection intervals, ft	2
iv.	WDI depth below WOC (h_{ow}), ft	5		
v.	WDI completion depth (h_{wd}), ft	3		
vi.	WRI depth below WOC, ft	38		
vii.	WRI completion depth (h_{wi}), ft	3		



Source: Jin (2009); modified by author.

Figure 4: Intervals of the producer well with DWL completion.

Furthermore, the water reinjection (q_{wi}) and polymer injection (q_{pi}) rates were determined using Material Balance Equation (MBE) by Havlena and Odeh (1963) with the assumptions that underground withdrawal was equal to the injected fluid (i.e., pressure maintenance), oil production was above bubble point pressure and there was no water production. Then, the established water reinjection and polymer injection rates expressions are expanded in Equations 1 and 2 respectively.

$$q_{wi} = q_{op}\left(\frac{B_o}{B_w}\right) \tag{1}$$

$$q_{pi} = q_{op}\left(\frac{B_o}{B_p}\right) \tag{2}$$

Here, B_o, B_w and B_p are oil, water and polymer formation volume factors respectively. The injector well was set to start polymer injection into the reservoir and aquifer after two years of oil production. Two scenarios of polymer injection from the injection well were evaluated. These scenarios were 6 and 3 months polymer injection intervals (i.e., INTEGRATED #1 and #2, respectively). The performance of the integrated water coning control approach was compared with Base-case (i.e., without water coning control completion) and DWL completion. The comparison was based on the water and oil production parameters obtained, namely, Field Water-cut (FWCT), Field Water Production Total (FWPT), Field Oil Production Rate (FOPR) and Field Oil Production Total (FOPT) as depicted in Figures 5 through 8. These results were used to assess the potential of using the integrated water coning control approach in thin oil rim reservoir in the Niger Delta.

III. DEVELOPED INTEGRATED WATER CONING CONTROL APPROACH

The performance of the integrated water coning control approach in thin oil rim reservoir model is indicated in the water and oil production parameters obtained. These were, Field Water-Cut (FWCT), Field Water Production Total (FWPT), Field Oil Production Rate (FOPR) and

Field Oil Production Total (FOPT). These are depicted in Figures 5 through 8. The water production parameters - FWCT and FWPT (Figures 5 and 6) showed that less water production was obtained with the integrated water coning control approach than downhole water loop (DWL) completion. Furthermore, these results indicated that lower water production was obtained from 3 months polymer injection interval (INTEGRATED #2) than from 6 months polymer injection interval (INTEGRATED #1). This less water production from the 3 months polymer injection interval is a result of reduced water mobility (Paul and Strom, 1988) in the water zone (aquifer) by the frequent injection of polymer gel. For the 6 months polymer injection interval, the mobility of the bottom-water was also reduced to suppress the upward movement of water (water coning tendency) but not as in the 3 month polymer injection interval, which is evident in the FWPT result obtained (Figure 6). Analysis of the water production parameters at 4108 days (i.e., about 11.25 years) as presented in Table 3 showed that the FWCT obtained from the DWL, INTEGRATED #1 and INTEGRATED #2 was 0.4542, 0.3179 and 0.2225, respectively. These values implied that there had been reduction by 37.99%, 56.60% and 69.63% from the DWL, INTEGRATED #1 and INTEGRATED #2 approaches respectively, when compared with the BASECASE FWCT of 0.7325. In addition, the cumulative water production (i.e., FWPT) obtained was 13.5 MMbbl, 8.10 MMbbl and 3.65 MMbbl for DWL, INTEGRATED #1 and INTEGRATED #2 approaches. This resulted in about 37.99%, 62.80% and 83.26% reduction of FWPT from DWL, INTEGRATED #1 and INTEGRATED #2 approaches respectively, when compared with the BASECASE FWPT of 21.8 MMstb.

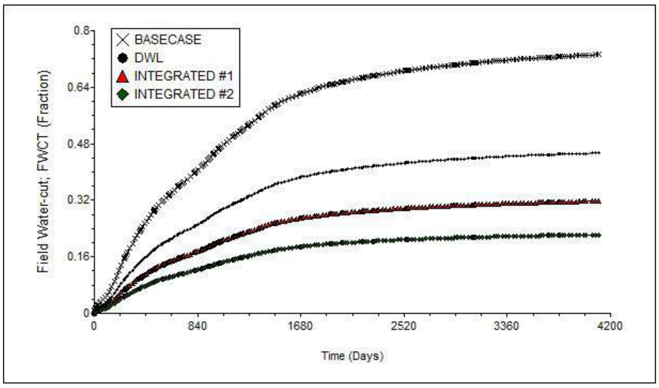


Figure 5: Comparison of the field water-cut (FWCT).

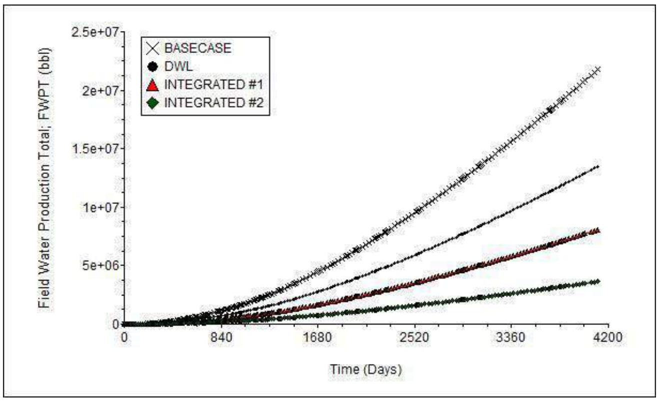


Figure 6: Comparison of the field water production total (FWPT).

Table 3: Water and oil production parameters obtained at 4108 days for the different reservoir completion scenarios

Simulations Run		Water Production Parameters		Oil Production Parameters	
		FWCT	**FWPT (bbl)**	**FOPR (bbl/day)**	**FOPT (bbl)**
i.	BASECASE	0.7325	21,777,366	1,178.656	1,640,346
ii.	DWL	0.4542	13,501,967	2,062.649	2,870,606
iii.	INTEGRATED #1	0.3179	8,101,180	3.197.105	4,449,440
iv.	INTEGRATED #2	0.2225	3,645,531	3.996.382	5,561,800

On the other hand, the oil production parameters: FOPR and FOPT responded to the less water production parameters obtained from the integrated water coning control approach. The field oil production rate and cumulative oil production (Figures 7 and 8) obtained from the integrated water coning control approach were higher than the DWL approach. The reason for this observation is that the integrated water coning control approach minimised water production; as noted in the FWCT and FWPT obtained (Figures 5 and 6), than DWL. Secondly, the injection of polymer into the reservoir (above WOC and below production interval) increased the sweep efficiency of the reservoir, resulting in increased oil production. The result further indicated that higher FOPR and FOPT were obtained from INTEGRATED #2 (i.e., 3 months polymer injection interval) than from INTEGRATED #1 (i.e., 6 months polymer injection interval). Again, this is attributed to the frequency at which the polymer is injected into the reservoir. Furthermore, the analysis of the oil production parameters at 4108 day; as presented in Table 3, showed that the FOPR obtained was 2,062.65 bbl/day, 3,197.11 bbl/day and 3,996.38 bbl/day, while the FOPT was 2.87 MMbbl, 4.45 MMbbl and 5.56 MMbbl from the DWL, INTEGRATED #1 and INTEGRATED #2, respectively. These values showed an increase by 75.0%, 171.25% and 239.06% from the DWL, INTEGRATED #1 and INTEGRATED #2 approaches respectively, when compared with the BASECASE FOPR and FOPT of 1,178.66 bbl/day and 1.64 MMbbl, respectively.

In summary, the simulation study revealed that the integrated water coning control approach minimised water production and improved oil production. From the water and oil production parameters result obtained, they indicated that there was significant reduction in the produced water by 83.26% and increased oil production of 239.06% at 3 months polymeric gel injection interval. Therefore, this integrated approach can be used as potential water coning control method in the Niger Delta thin oil rim reservoirs to reduce water production and increase oil recovery from them.

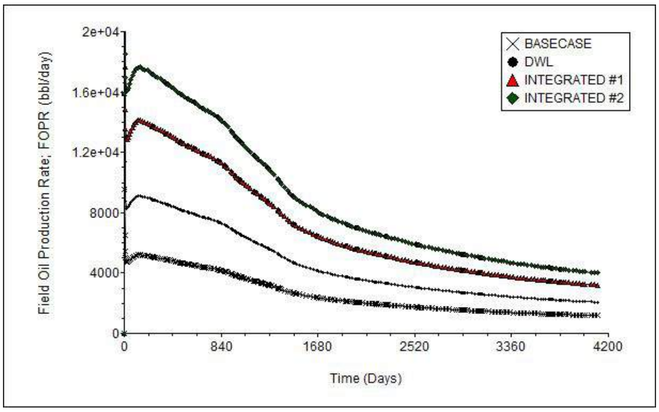


Figure 7: Comparison of the field oil production rate (FOPR).

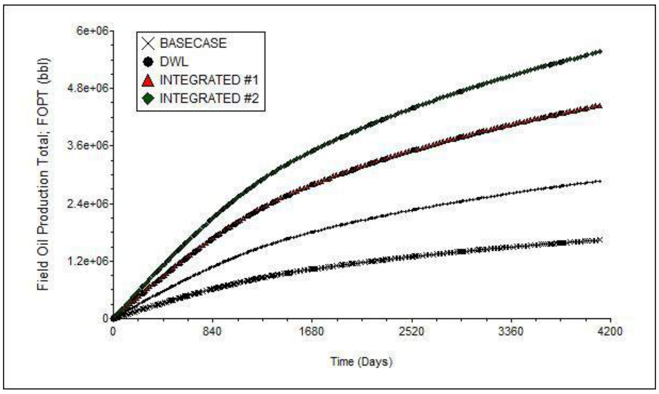


Figure 8: Comparison of the field oil production total (FOPT).

VI. CONCLUSION

Oil production from thin oil rim reservoirs is mostly characterized by early water breakthrough which hinders its overall oil recovery potential; hence, the integrated water coning control approach that combined downhole water loop (DWL) technology and polymeric gel injection was developed. From the simulation results obtained, the following conclusions were drawn:

i. The developed integrated approach reduced water production by 62.80% and 83.26% at 6 and 3 months polymeric gel injection intervals;
ii. The integrated water coning control approach improved oil production by 171.25% and 239.06% at 6 and 3 months polymer injection intervals; and

iii. The developed integrated water coning control approach performed better (i.e., reduce produced water and improve oil recovery) than DWL approach; as it reduced water production by 38.0% and improved oil production by 75.0%.

From the foregoing, huge volume of water handling at the surface and disposal challenges are overcome with the developed integrated approach compared to other existing methods. Therefore, the developed integrated water coning control approach can be used as a veritable tool for minimizing water coning tendency to improve oil recovery from thin oil rim reservoirs in the Niger Delta.

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