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Kyewords: capillary transition zone; non-capillary transition zone; reservoir wettabilities; water coning; oil rim reservoir.

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ABSTRACT

Oil zones in oil rim reservoirs are mostly in the transition zones; the region where relative permeability and capillary pressure are water saturation dependent, because of thin oil resource interval. These oil zones are with mobile water saturation, as oil production from rim reservoirs is characterized by early water production from water coning phenomenon. In this study, the influence of the capillary transition zone (CTZ) and reservoir wettability on water coning in oil rim reservoir were simulated using Black-oil Simulator – Eclipse-100. Capillary pressure – water saturation data were obtained from an oil rim reservoir in the Niger Delta. The different reservoir wettabilities (water-wet, mixed-wet, and oil-wet), capillary pressure – saturation and relative permeabilities – saturation input data for the simulation were modeled based on Skaevenland *et al.* (2000) and Brooks and Corey (1966) correlations using multivariable numerical optimization approach. The simulation results from the integrated oil rim reservoir model indicated that the capillary transition zone (CTZ) increases water production and reduces oil recovery potential than non-capillary transition zone (NCTZ) in the oil rim reservoir. Additionally, comparing the reservoir wettabilities showed that water-cut from water-wet was 0.961 and 0.733, mixed-wet 0.920 and 0.655, and oil-wet 0.920 and 0.631 for CTZ and NCTZ, respectively. This result depicted that water-wet wettability for both CTZ and NCTZ in oil rim reservoir result in high water production than in mixed-wet and oil-wet wettabilities. Furthermore, cumulative oil production from water-wet was 1.425 MMstb and 1.640 MMstb, mixed-wet 1.770 MMstb and 2.036 MMstb, and oil-wet 1.757 MMstb and 1.985 MMstb for CTZ and NCTZ. Thus, the presence of CTZ, especially in the water-wet reservoir, influences the severity of water coning tendency in oil rim reservoir(s) than in mixed-wet and oil-wet reservoir wettability.

Keywords: capillary transition zone; non-capillary transition zone; reservoir wettabilities; water coning; oil rim reservoir.

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I. INTRODUCTION

Oil production from oil rim reservoirs is mostly from capillary transition zones. These zones occur between two phases due to the capillary pressure generated when the fluids (oil and water) are immiscible (Larson *et al.*, 2000). In oil rim reservoirs, these zones vary from a few meters to several hundred meters (Masalmeh and Oedai, 2000) and contain a significant proportion of the oil in place (Jackson *et al.*, 2005; Iglauer and Muggeridge, 2013). Most often, the zone exhibits variable wettability with the most water-wet conditions found at the base and the most oil-wet condition at the top of the oil rim reservoir (Hamon, 2000; Masalmeh, 2000). Parker and Rudd (2000) maintained that reservoir wettability variations within the transition zone are principally controlled by the increase in water saturation with the capillary transition depth.

In the production of oil and gas from petroleum reservoirs, wettability has a significant impact on flow during oil recovery and upon the volume and distribution of the residual oil in the reservoir (Jadhunandan and Morrow, 1995). For oil rim reservoirs which are prone to water coning phenomenon, wettability variation is more present due to its thin oil resource interval (depth). Studies on wettability had focused on wettability alteration as it effects fluid distribution (i.e., water and oil saturation) and oil mobility/recovery from the reservoir(s). Zhou *et al.* (2000) opined that changes in wettability induce changes in capillary pressure in the reservoir. Therefore, the significance of wettability in reservoir fluid recovery cannot be over emphasized in the production of hydrocarbons. On the other hand, several studies had been carried out on water coning tendency in oil rim reservoirs. The available works focused on water coning parameter prediction models (i.e., critical oil rate, water breakthrough time, etc.) and attenuation approaches, namely; horizontal well, downhole oil-water separation (DOWS), downhole water sink (DWS), among others. Okon *et al.* (2018) reported that some of these water coning attenuation methods have received field application.

Some oil producing companies consider development and oil production from oil rim reservoirs uneconomical because of its limited oil zone and its associated production challenges (i.e., early water breakthrough). Sarwaruddin *et al.* (online) had also reported that oil recovery from transition zones are not economical in many cases, however for a low permeability reservoir, the entire reservoir or a substantial part of it might become a potential target for recovery. Therefore it is pertinent to put in place adequate development and production strategies to maximize oil recovery from transition zones and in oil rim reservoir(s) as well. As earlier alluded, wettability has remarkable control on fluid flow and distribution in the pore space of the reservoir during oil recovery. Regrettably, limited or no work has been reported evaluating the influence of capillary transition zone and reservoir wettability on water coning tendency in the oil rim reservoir. Hence, based on a simulation study, this work evaluates the influence of capillary transition zone and reservoir wettability on water coning in an oil rim reservoir.

II. MATERIALS AND METHODS

According to Mogbo (2010), most oil rim reservoirs are found in the capillary transition zone. Therefore, fluid flow in this reservoir's zone is predominantly dominated by capillary pressure and its wettability (Okon, 2019). To assess the influence of capillary transition zone and reservoir wettability on water coning tendency in oil rim reservoir, fluid saturation and capillary pressure data from oil rim reservoir in the Niger Delta were obtained (Table A.1). The correlations developed by Skjaeveland *et al.* (2000) were used to fit the data obtained to various reservoir wettabilities using a multivariable numerical optimization approach. Thus, the fitted capillary pressure correlations for the respective reservoir's wettability are presented in Equations 1 through 3. The predictions of the fitted correlations (Equations 1 through 3), which are used in the simulation runs, are presented in Table A.2 (Appendix A).

i. water-wet:

$$P_c = \frac{0.0063}{\left[\dfrac{S_w - S_{wr}}{1 - S_{wr}}\right]^{1.3215}} \tag{1}$$

ii. mixed-wet:

$$P_c = \frac{0.1482}{\left[\dfrac{S_w - S_{wr}}{1 - S_{wr}}\right]^{0.6469}} - \frac{0.1524}{\left[\dfrac{S_o - S_{or}}{1 - S_{or}}\right]^{0.0103}} \tag{2}$$

iii. oil-wet:

$$P_c = \frac{0.0235}{\left[\dfrac{S_o - S_{or}}{1 - S_{or}}\right]^{0.1259}} \tag{3}$$

Also, the relative permeabilities: water relative permeability (k_{rw}) and oil relative permeability (k_{ro}) for the simulations study were determined from the correlations (Equations 4 and 5) established by Brooks and Corey (1966) in Eigestad and Larsen (2000). These predictions are presented in Table A.3 (Appendix A).

$$k_{rw} = S_{nw}^{3+2a_w} \quad (4)$$

$$k_{ro} = \left[1 - S_{nw}^{2a_w+1}\right]\left(1 - S_{nw}\right)^2 \quad (5)$$

Where S_{nw} is the normalized saturation expressed as;

$$S_{nw} = \left[\frac{S_w - S_{wr}}{1 - S_{wr} - S_{or}}\right] \quad (6)$$

Then the relative permeability - water saturation profile for the various reservoir wettabilities is presented in Figures 1 through 3. Thus, the capillary pressures predicted by the fitted correlations and their corresponded relative permeabilities (i.e., k_{rw} and k_{ro}) for the various reservoir wettabilities were used for the simulations study. They were incorporated in the Eclipse-100 input data file. The simulations were run using the reservoir model in Figure 4. The reservoir model was simulated with the presence of capillary transition zone scenario using the Keywords "HYPC, HYKR, and SWATINIT" in the Eclipse-100 input data file and without capillary transition zone scenario. The simulation results obtained in term of Field Water-cut (FWCT), Field Oil Production Rate (FOPR) and Field Oil Production Total (FOPT) were used to assess the influence of the capillary transition zone and reservoir wettability on water coning tendency in oil rim reservoirs. These results obtained are presented in Figures 5 through 24.

III. RESULTS AND DISCUSSION

The relative permeability – saturation curves obtained for the various reservoir wettabilities are presented in Figures 1 through 3. For the water-wet reservoir (Figure 1), the water relative permeability (k_{rw}) and oil relative permeability (k_{ro}) curves intersected at about 0.6 water saturation (S_w). This point of intersection value (i.e., 0.6) implied that the reservoir wettability is preferentially water-wet (Zolotuklun and Ursin, 2000). Also, for the mixed-wet reservoir, the water relative permeability (krw) and oil relative permeability (k_{ro}) curves intersected at about 0.5 water saturation (S_w) (Figure 2), which indicated mixed (natural) wettability. Furthermore, the oil-wet relative permeability – saturation curve (Figure 3) indicated preferential oil-wet reservoir, as the water relative permeability (k_{rw}) and oil relative permeability (k_{ro}) curves intersected that about 0.40 water saturation (S_w). Hence, these established reservoir wettabilities based on relative permeability – saturation curve justified the use of the estimated capillary pressure and their corresponded relative permeabilities (i.e., k_{rw} and k_{ro}) data in the simulated study of the capillary transition zone and reservoir wettability influence on water coning in oil rim reservoirs.

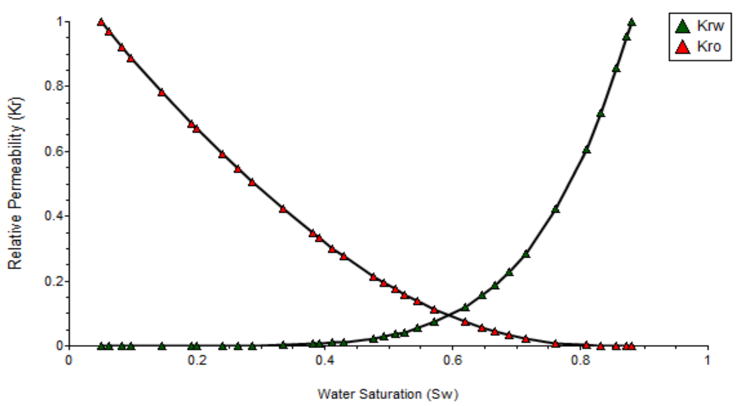

Figure 1: Oil and water relative permeability curve for water-wet oil rim reservoir

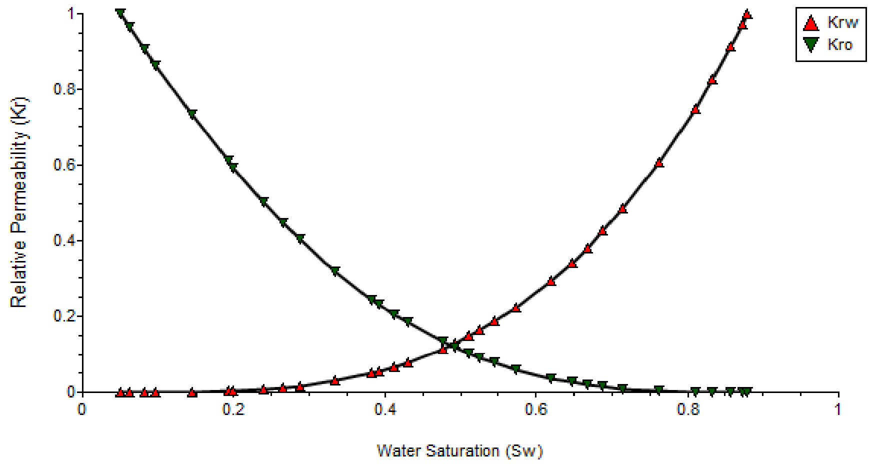

Figure 2: Oil and water relative permeability curve for mixed-wet oil rim reservoir

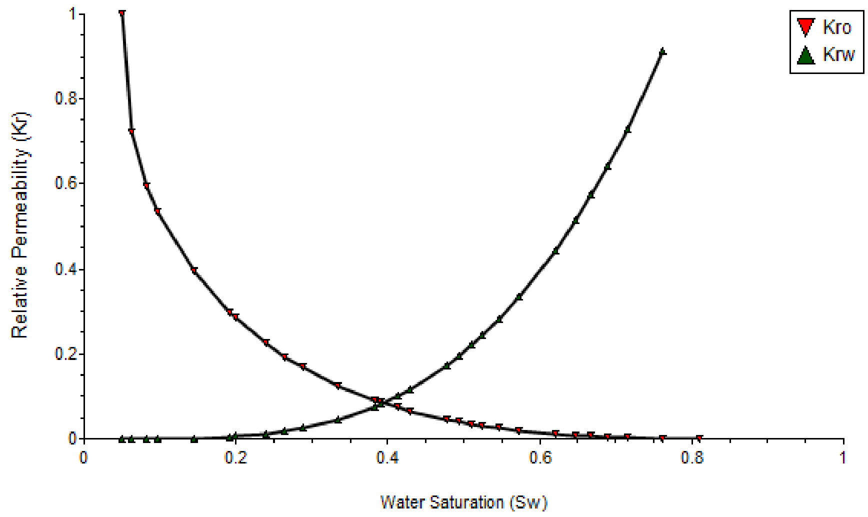

Figure 3: Oil and water relative permeability curve for oil-wet oil rim reservoir

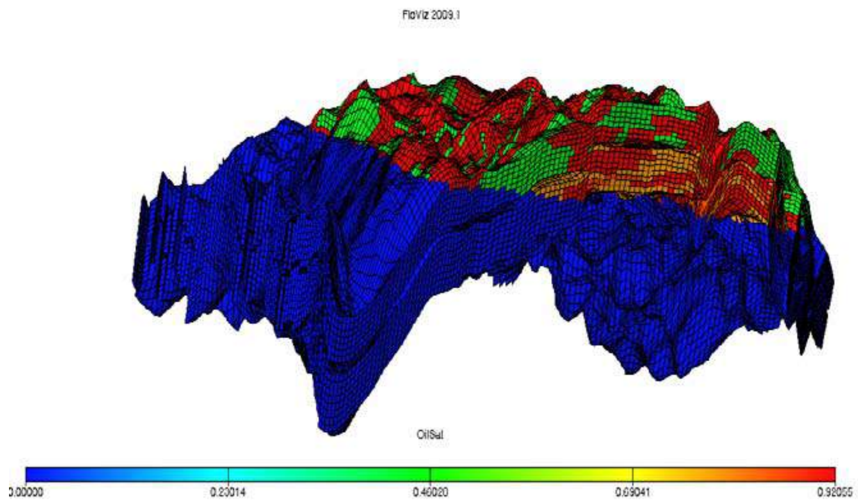

Figure 4: Integrated Reservoir Model

3.1 Capillary Transition Zone Influence

Figures 5 through 16 and Table 1 present the comparison of Capillary Transition Zone (CTZ) and Non-Capillary Transition Zone (NCTZ) influences on water coning phenomenon in a modeled oil rim reservoir with different wettability: water-wet, mixed-wet, and oil-wet. The water production parameters obtained, that is, field water-cut (FWCT) and field water production rate (FWPR) from the various reservoir wettabilities; as depicted in Figures 5 and 8 (water-wet), Figures 9 and 12 (mixed-wet) and Figure 13 and 16 (oil-wet), indicate higher FWCT and FWPR from the reservoir with capillary transition zone (CTZ) than the one with no capillary transition zone (NCTZ). This implied that the reservoir with CTZ produced more water than the reservoir with NCTZ.

A look at Table 1 indicates 0.96 field water-cut for CTZ and 0.733 for NCTZ in the water-wet reservoir. This value is about 23.65% decreased for the water-cut obtained in NCTZ. Also, for mixed and oil-wet reservoirs, the field water-cut obtained resulted in 28.80% and 31.41% decrease in NCTZ, respectively. The reason for this high (excessive) water production from the reservoir with CTZ than NCTZ is because the CTZ in the reservoir contains more movable (free) water saturation than NCTZ. Thus, this water content in the CTZ is produced alongside with the breakthrough, which resulted in high water production. Consequently, the high (excessive) water production from the reservoir with CTZ hindered its oil production potentials. The oil production parameters: field oil production rate (FOPR) and field oil production total (FOPT) obtained from the various reservoir wettabilities; as shown in Figures 7 and 8 (water-wet), Figures 11 and 12 (mixed-wet) and Figure 15 and 16 (oil-wet), indicated that reservoir with NCTZ had high FOPR and FOPT than reservoir with CTZ.

Table 1 indicates FOPR of 890.0 bbl/day for CTZ and 1,178.65 bbl/day for NCTZ in the water-wet reservoir. This value is about 24.49% increase for the FOPR obtained in NCTZ. Also, the FOPR obtained for mixed and oil-wet reservoirs resulted in 29.11% and 28.07% increase in NCTZ, respectively. This result means more oil was produce from the modeled oil rim reservoir with NCTZ than the one with CTZ. This observation was attributed to the high water production experienced in the CTZ reservoir than the NCTX reservoir, as excessive water production from water coning results in low hydrocarbon recovery (Mahgoup and Khair, 2015).

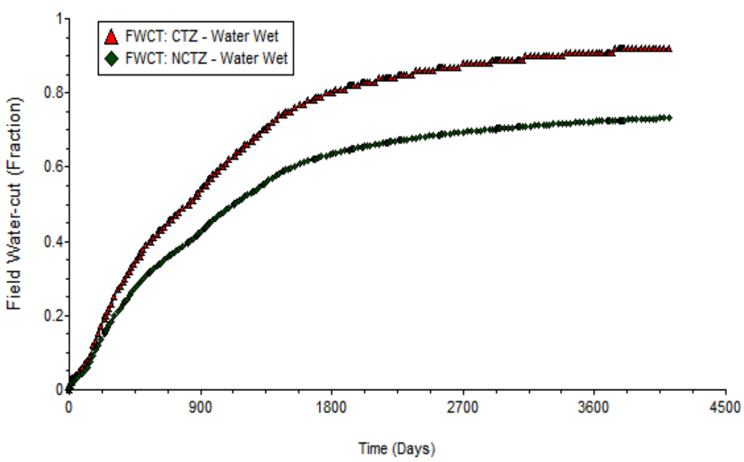

Figure 5: Comparison of field water-cut in water wet reservoir

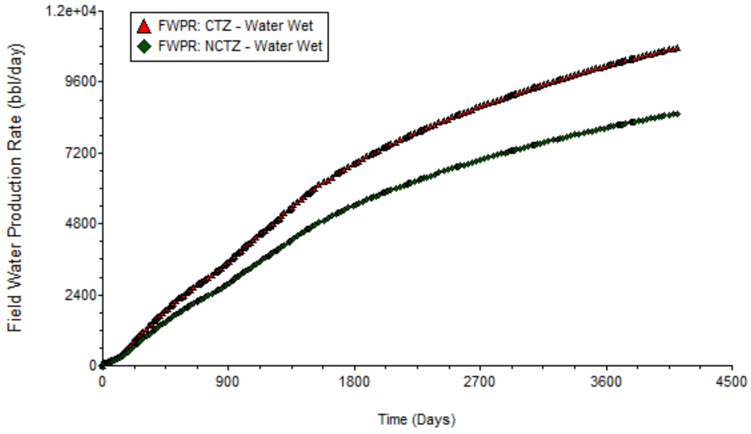

Figure 6: Comparison of field water production rate in water wet reservoir

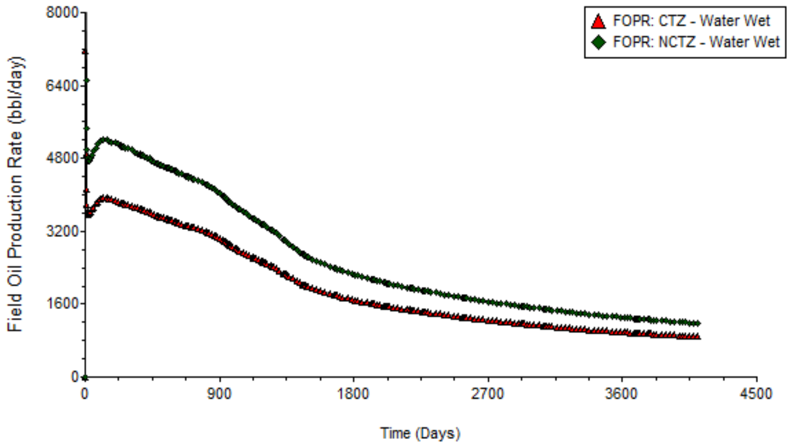

Figure 7: Comparison of field oil production rate in water wet reservoir

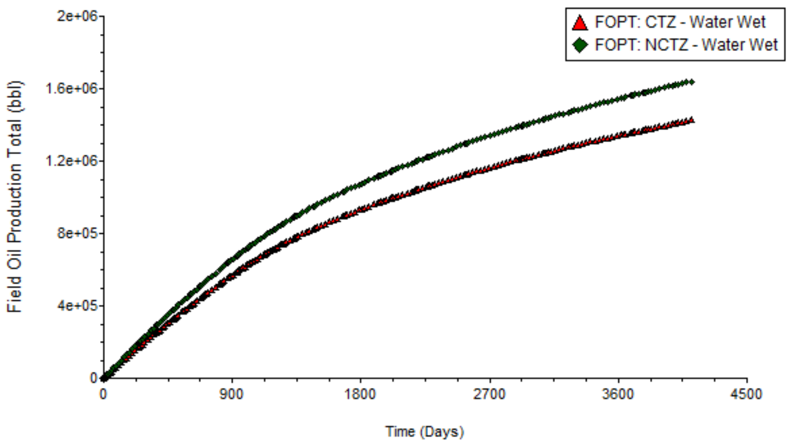

Figure 8: Comparison of field oil production total in water wet reservoir

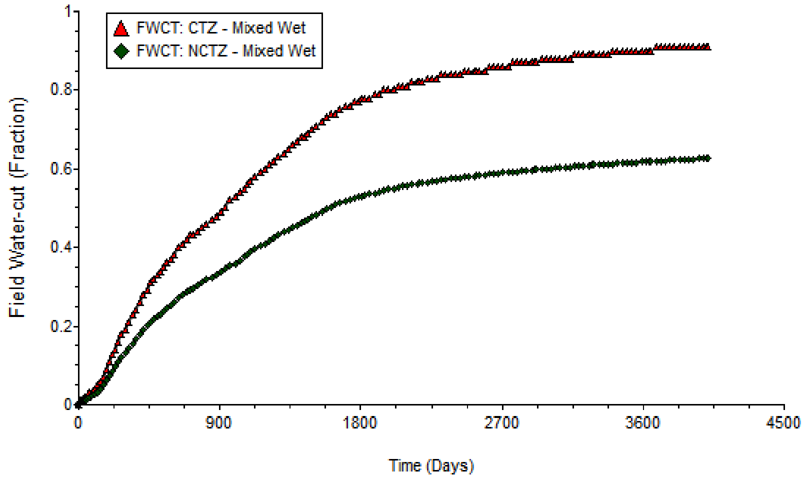

Figure 9: Comparison of field water-cut in mixed wet reservoir

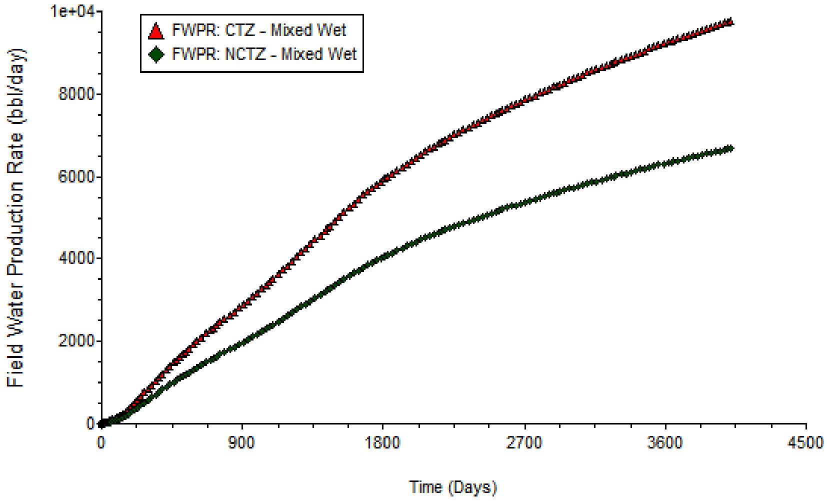

Figure 10: Comparison of field water production rate in mixed wet reservoir

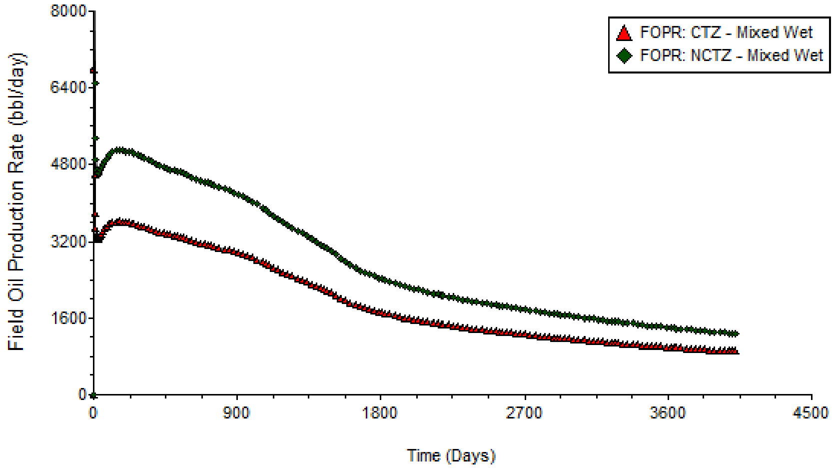

Figure 11: Comparison of field oil production rate in mixed wet reservoir

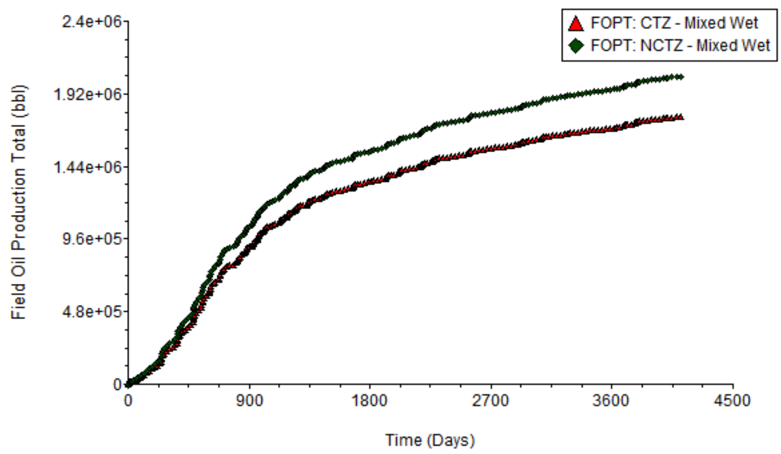

Figure 12: Comparison of field oil production total in mixed wet reservoir

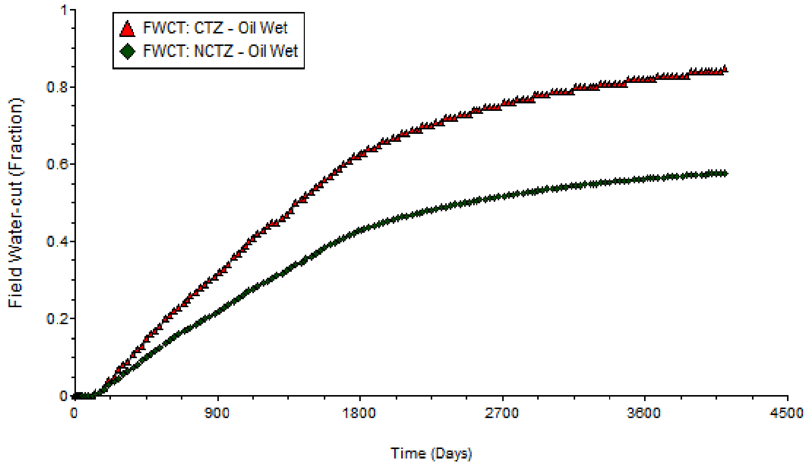

Figure 13: Comparison of field water-cut in oil wet

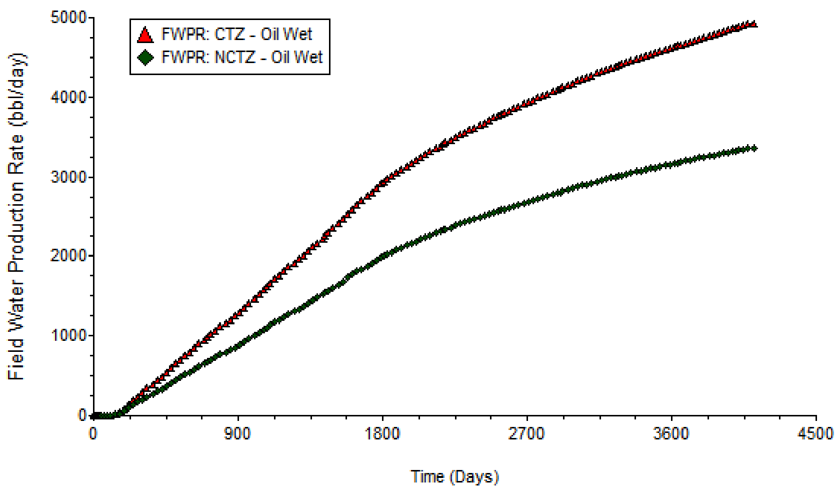

Figure 14: Comparison of field water production rate in oil wet reservoir

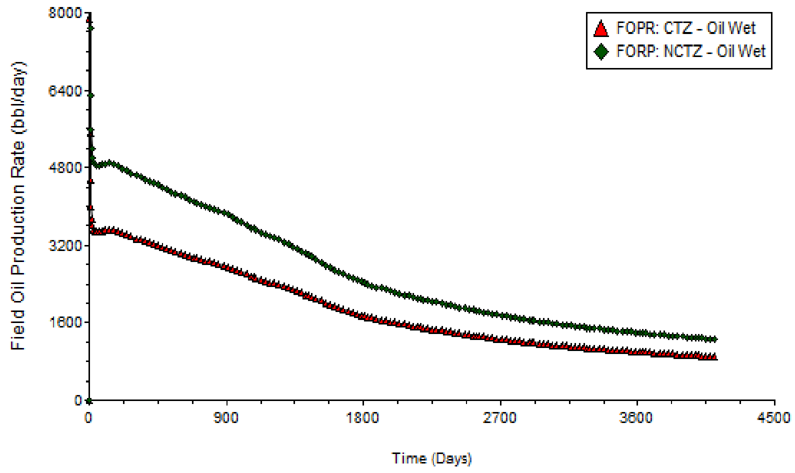

Figure 15: Comparison of field oil production rate in oil wet Reservoir

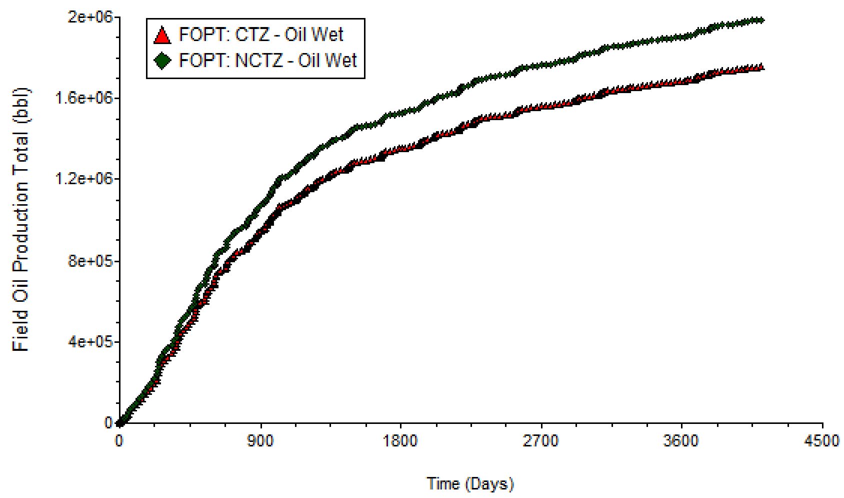

Figure 16: Comparison of field oil production total in oil wet Reservoir

Table 1: Water and oil production parameters at 4108 days for the different reservoir wettability and scenarios

	Production Parameters	Water-wet		Mixed-wet		Oil-wet	
		CTZ	NCTZ	CTZ	NCTZ	CTZ	NCTZ
i.	FWCT, *fraction*	0.961	0.733	0.920	0.655	0.920	0.631
ii.	FWPR, *bbl/day*	10,771	8,541.24	12,501	8,550.62	6,261.0	4,276.26
iii.	FOPR, *bbl/day*	890.0	1178.65	549.0	774.42	513.0	713.20
iv.	FOPT,*bbl*	1,426,388.2	1,640,346.5	1,769,959.0	2,035,452.9	1,756,723.0	1,985,097.0

3.2 Reservoir Wettability Influence

Figures 17 through 20 show the reservoir wettability influence on water coning in oil rim reservoir(s) with capillary transition zone (CTZ), while Figures 21 through 24 depict the same influence with no capillary transition zone (NCTZ) in the reservoir. The water production parameters, that is, field water-cut (FWCT) and field water production rate (FWPR) obtained for both reservoir scenarios (i.e., CTZ and NCTZ) indicated that higher water production was obtained in water-wet reservoir than mixed and oil-wet reservoirs (Figures 17 and 18 for CTZ and Figures 21 and 22 for NCTZ). This observation attests to the fact that water-wet reservoirs enable the mobile water content in the reservoir to flow more freely than in the mixed and oil-wet reservoir(s). Thus, the easier flow in the water-wet reservoir is due to less surface tension between the reservoir rock and wetting phase (i.e., water) and interfacial tension between the wetting and non-wetting phase, that is, water and oil (Zolotuklun and Ursin, 2000).

The field oil production rate (FOPR) obtained from CTZ and NCTZ reservoir scenarios (Figures 19 and 21, respectively) depicted higher oil production rates in the water-wet reservoir than mixed and oil-wet reservoirs. On the other hand, the field oil production total (FOPT) or cumulative oil production obtained from both reservoir scenarios (i.e., CTZ and NCTZ) was higher for mixed and oil-wet reservoirs than the water-wet reservoir. This was because from both reservoir scenarios: CTZ and NCTZ, the FWCT and FWPR obtained indicated higher water production in water-wet reservoir than mixed and oil-wet reservoirs, which in turn affected recovery potential of the reservoir and resulted in the low oil production from the water-wet reservoir (Ayeni, 2008; Mahgoup and Khair, 2015; Okon *et al.*, 2018). Also, the results obtained revealed that the difference in mixed and oil-wet reservoirs' influence from both reservoir scenarios on the oil production was at the early period (years) of production. Later on, these reservoir wettabilities give about the same oil production rate and cumulative oil production as production continues; the mixed-wet reservoir seems to produce like the oil-wet reservoir (Figures 19 and 20 for CTZ and Figures 23 and 24 for NCTZ).

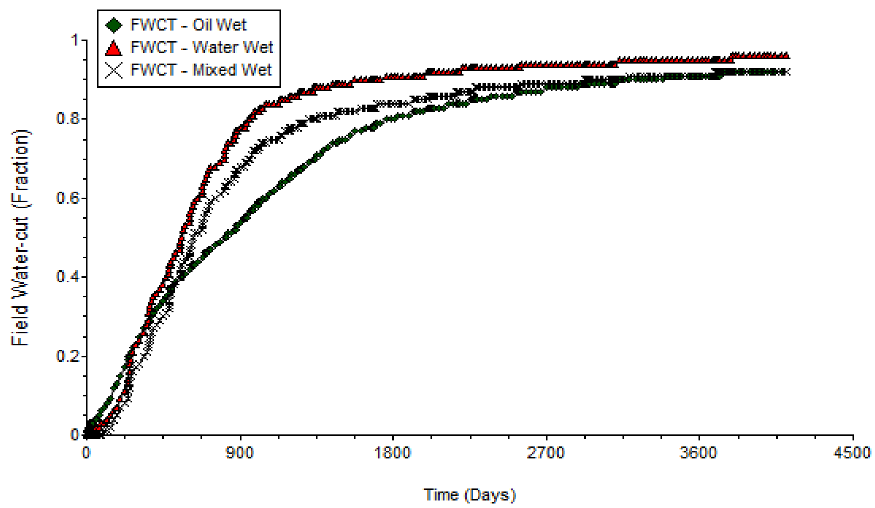

Figure 17: *Comparison of field water-cut (capillary transition zone)*

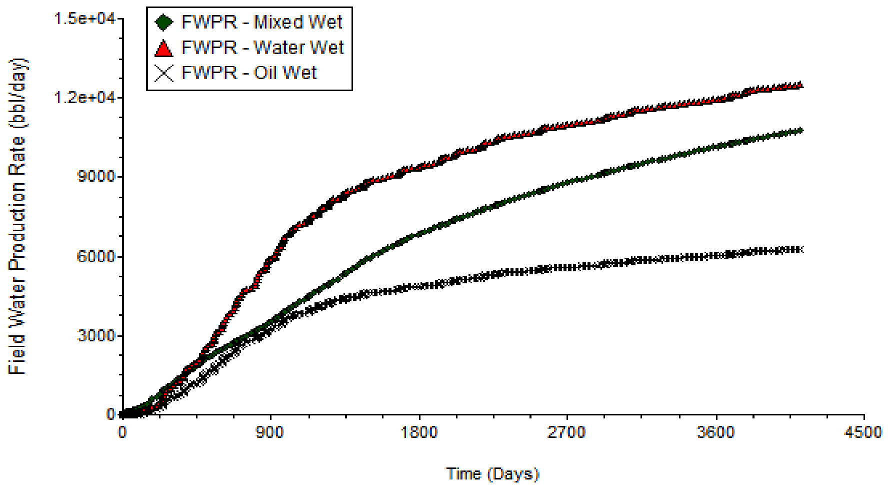

Figure 18: Comparison of field water production rate (capillary transition zone)

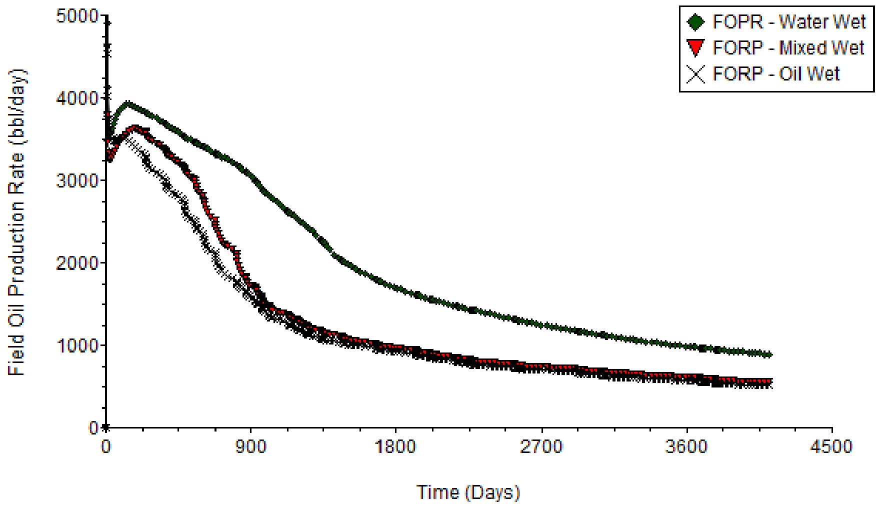

Figure 19: Comparison of field oil production rate (capillary transition zone)

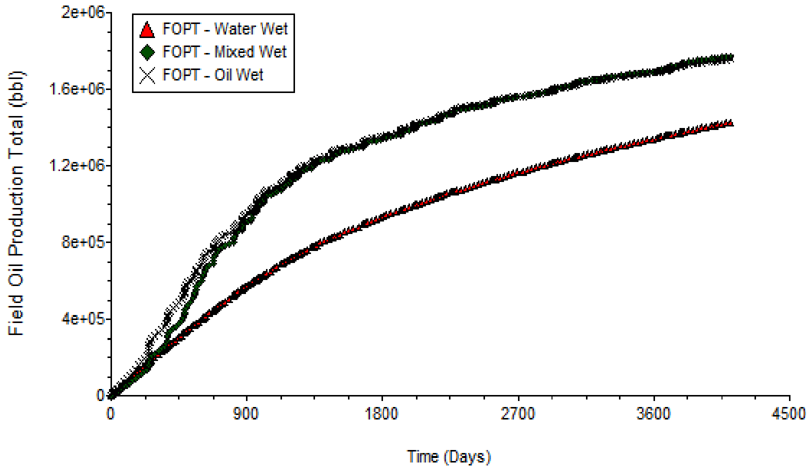

Figure 20: Comparison of field oil production total (capillary transition zone)

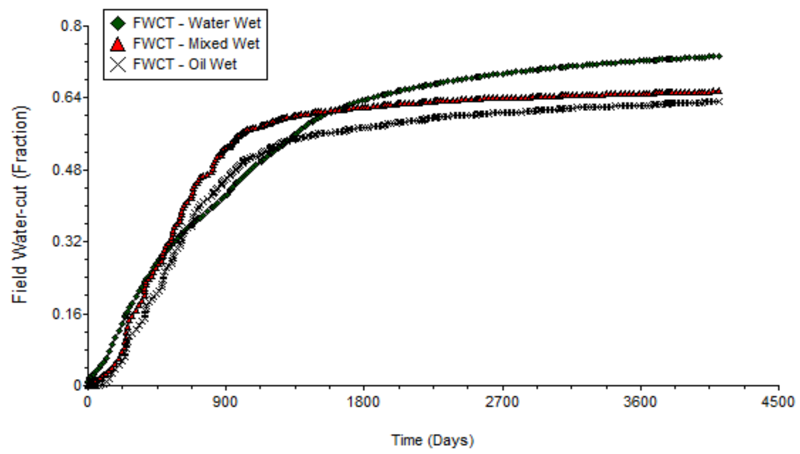

Figure 21: Comparison of field water-cut (no capillary transition zone)

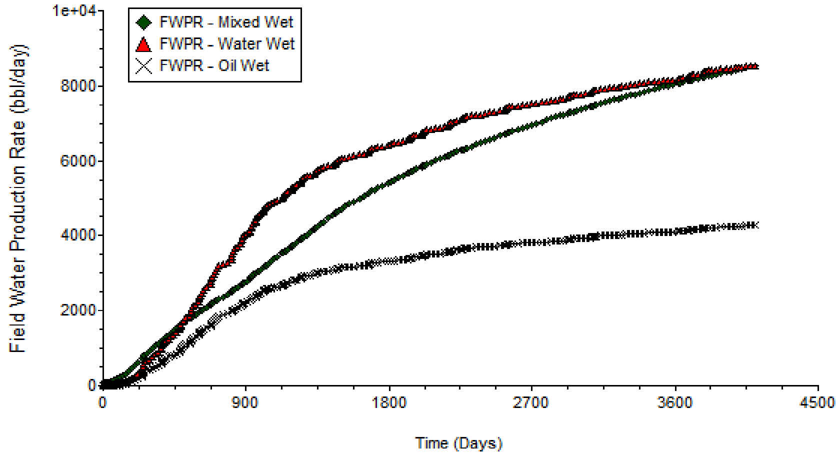

Figure 22: Comparison of field water production rate (no capillary transition zone)

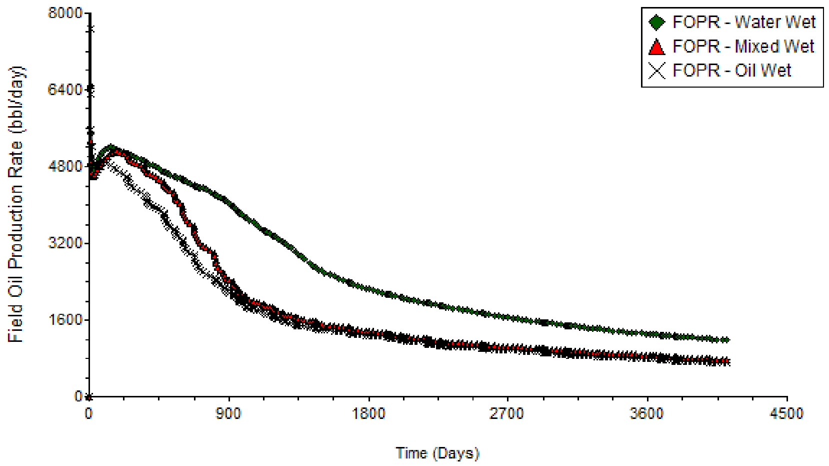

Figure 23: Comparison of field oil production rate (no capillary transition zone)

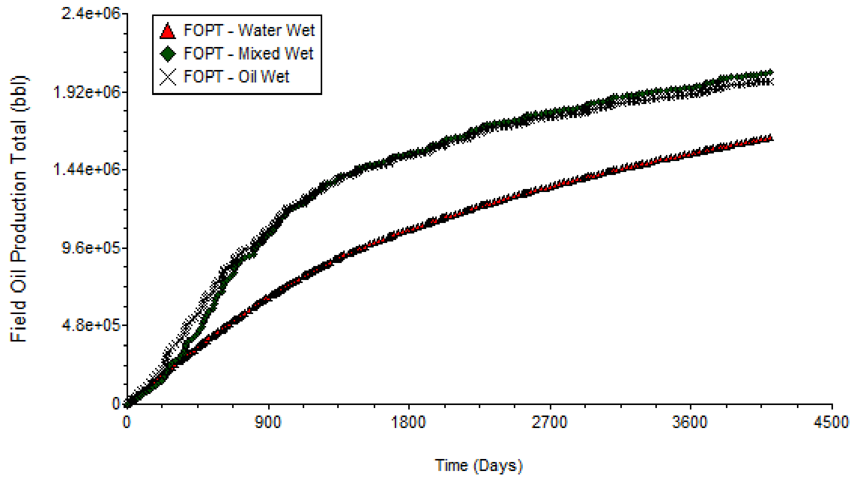

Figure 24: Comparison of field oil production total (no capillary transition zone)

IV. CONCLUSION

The simulation study to evaluate the influence of capillary transition zone and reservoir wettability on water coning in oil rim reservoir(s) revealed that: capillary transition zone increase/s water production and early water breakthrough in oil rim reservoirs, while the absence of this zone delay/s the aforementioned in oil rim reservoir;

i. Capillary transition zone reduces the oil recovery potential of oil rim reservoir(s); and
ii. Reservoir wettability: water-wet reservoir exhibits greater influences on the severity of water coning tendency in oil rim reservoir(s) than mixed-wet and oil-wet reservoirs.

Hence, the extent of the capillary transition zone and reservoir wettability type are important factors to be considered in oil rim reservoir(s) development to achieve optimum oil recovery potential of the reservoir.

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Appendix A

Table A.1: Field capillary pressure and water saturation data

Fluid Saturation (S_w)	Capillary Pressure (P_c)	Fluid Saturation (S_w)	Capillary Pressure (P_c)
0.050	2.020	0.493	0.075
0.062	2.001	0.511	0.071
0.083	1.621	0.525	0.064
0.098	0.987	0.546	0.060
0.145	0.489	0.573	0.052
0.193	0.317	0.620	0.042
0.200	0.298	0.647	0.036
0.240	0.230	0.668	0.033
0.265	0.198	0.689	0.030
0.288	0.177	0.715	0.025
0.335	0.141	0.763	0.017
0.383	0.114	0.810	0.010
0.392	0.103	0.833	0.008
0.413	0.099	0.858	0.003
0.430	0.094	0.873	0.003
0.478	0.078	0.880	0.001

Table A.2: Predicted capillary pressure for simulations study

Water Saturation (S_w)	Reservoir Wettability		
	Water wet	**Mixed wet**	**Oil wet**
0.050	2.0202	2.3533	2.0201
0.062	0.1312	1.1499	2.0010
0.083	0.0768	0.8764	1.6210
0.098	0.1312	0.5046	0.9870
0.145	0.0768	0.3529	0.4890
0.193	0.0525	0.3363	0.3171
0.200	0.0446	0.2669	0.2980
0.240	0.0391	0.2346	0.2301
0.265	0.0307	0.2103	0.1978
0.288	0.0307	0.1699	0.1771
0.335	0.0251	0.1391	0.1409
0.383	0.0210	0.1337	0.1145
0.493	0.0148	0.0829	0.0746
0.511	0.0138	0.0782	0.0712
0.525	0.0138	0.0718	0.0639
0.546	0.0123	0.0642	0.0601
0.573	0.0123	0.0522	0.0522
0.620	0.0111	0.0458	0.0420
0.647	0.0106	0.0413	0.0364
0.668	0.0100	0.0369	0.0329
0.689	0.0092	0.0318	0.0295
0.715	0.0092	0.0235	0.0247
0.763	0.0084	0.0156	0.0171
0.833	0.0076	0.0076	0.0076
0.858	0.0075	0.0043	0.0031
0.873	0.0076	0.0015	0.0029
0.880	0.0075		0.0000

Table A.3: Estimated relative permeabilities for the various reservoir's wettability

Water Saturation (S_w)	Reservoir Wettability					
	Water wet		Mixed wet		Oil wet	
	Relative Permability					
	k_{rw}	k_{ro}	k_{rw}	k_{ro}	k_{rw}	k_{ro}
0.050	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000
0.062	0.0000	0.9665	0.0000	0.9712	0.0000	0.9665
0.083	0.0000	0.9058	0.0000	0.9215	0.0000	0.9058
0.098	0.0001	0.8641	0.0000	0.8876	0.0001	0.8641
0.145	0.0009	0.7322	0.0001	0.7788	0.0009	0.7322
0.193	0.0032	0.6105	0.0005	0.6741	0.0032	0.6105
0.200	0.0038	0.5924	0.0006	0.6580	0.0038	0.5924
0.240	0.0083	0.5007	0.0018	0.5744	0.0083	0.5007
0.265	0.0124	0.4478	0.0030	0.5243	0.0124	0.4478
0.288	0.0171	0.4032	0.0046	0.4807	0.0171	0.4032
0.335	0.0309	0.3180	0.0102	0.3940	0.0309	0.3180
0.383	0.0511	0.2450	0.0197	0.3152	0.0511	0.2450
0.392	0.0560	0.2317	0.0222	0.3005	0.0560	0.2317
0.413	0.0679	0.2041	0.0287	0.2691	0.0679	0.2041
0.430	0.0788	0.1834	0.0349	0.2450	0.0788	0.1834
0.478	0.1156	0.1327	0.0579	0.1838	0.1156	0.1327
0.493	0.1298	0.1183	0.0675	0.1659	0.1298	0.1183
0.511	0.1478	0.1030	0.0801	0.1464	0.1478	0.1030
0.525	0.1629	0.0920	0.0910	0.1321	0.1629	0.0920

0.546	0.1875	0.0769	0.1096	0.1122	0.1875	0.0769
0.573	0.2220	0.0604	0.1371	0.0898	0.2220	0.0604
0.620	0.2946	0.0368	0.1992	0.0567	0.2946	0.0368
0.647	0.3425	0.0266	0.2430	0.0418	0.3425	0.0266
0.668	0.3822	0.0203	0.2809	0.0323	0.3822	0.0203
0.689	0.4275	0.0148	0.3255	0.0239	0.4275	0.0148
0.715	0.4864	0.0096	0.3861	0.0158	0.4864	0.0096
0.763	0.6087	0.0035	0.5192	0.0059	0.6087	0.0035
0.810	0.7509	0.0007	0.6850	0.0013	0.7509	0.0007
0.833	0.8263	0.0002	0.7773	0.0004	0.8263	0.0002
0.858	0.9145	0.0000	0.8887	0.0000	0.9145	0.0000
0.873	0.9728	0.0000	0.9643	0.0000	0.9728	0.0000
0.880	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000