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UN-RECOVERED OIL BY VERTICAL WELLS WITH WATER CONING – ASSESSMENT, PREDICTION AND REMEDIATION

1. BACKGROUND

Oil bypassing is a significant problem in U.S. reservoirs. Of the 582 billion barrels of oil in-place in discovered fields in the U.S., 208 billions have been already produced or proven, leaving behind 374 billion barrels of oil [1], or 64.3% of the oil in place. Water invasion to wells causing premature well shut-off is considered a major reason for the by-passing. On average in the United States, more than seven barrels of water are produced for each barrel of oil [2]. Water invasion occurs in the bottom and edge-water systems. Our recent research work demonstrated the mechanism of water invasion in edge-water drive reservoirs – water underruning [3, 4]. In the bottom-water systems, oil bypassing results from water coning.

Varieties of techniques have been used to reduce water invasion. Typically, they are classified as mechanical and chemical methods. By some authors, the mechanical methods involve the use of packers, bridge plugs, well abandonment, infill drilling, pattern flow control and horizontal wells [5]. Among the most commonly used chemical methods are cement, sand, calcium carbonate, gels, resins, foams, emulsions, particulates, precipitates, microorganisms and polymers [5]. Thus, the effective strategy for selecting a proper method should involve a careful diagnosis of the excessive water problem. Seright et al. [5] proposed a methodology to attack the various types of water problems by categorizing them from the least to most difficult. Water coning and underruning were considered the most difficult with no easy, low-cost solution. The authors maintained that gel treatments will almost never work for coning and underruning problems. Their observation was based on extensive reservoir and completion engineering studies and analyses of many field applications.

Gel treatments target the reduction of water inflow to wells implicitly assuming that oil inflow would increase. In case of water coning and underruning the flow of water is an integral part of flow deliverability and, as such, cannot be stopped or reduced without re-

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ducing the oil flow. Thus, strategies studied in this paper address the increased/accelerated oil recovery, instead of reduced water production. Two different methods for recovery optimization are studied using numerical simulation: changes in well penetration and dual completion installation featuring downhole water sink. These solutions involve optimization of well completion's length and placement. The effect of a well penetration is studied first, and then compared with downhole water sink (DWS). The two types of well completions are compared for new and watered out wells in bottom and edge-water systems.

2. MODEL DESCRIPTION

Figure 1 shows schematics of the numerical model used to study well completion strategy for the bottom-water systems. A 2-D (R, Z) radial-cylindrical simulation grid was created to represent an idealized single-well drainage area. The model was created using the reservoir simulator "IMEX", developed by Computer Modeling Group (CMG) [6]. No divisions were considered in the „angular" direction. Block sizes were increased so that the radial locations of the block centers are roughly in geometric progression. The number of grid blocks has been optimized with a grid sensitivity analysis. In the analysis, three different levels of grid blocks were considered for both the radial and the vertical directions. The analysis showed that accurate results could be obtained with a total of 3060 grid blocks: 51 grid blocks in the radial direction and 60 in the vertical direction.

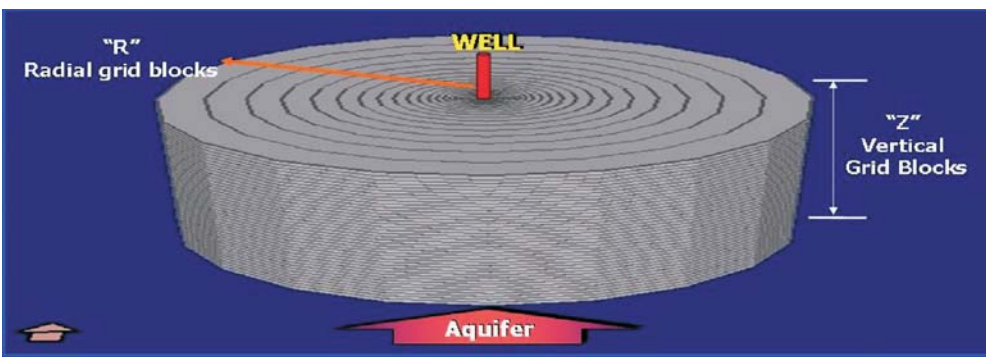

Fig. 1. Radial simulation model

Radial concentric geometry, used in this work, is the most common approach to study wells operation in the bottom-water-drive systems [7, 8, 9] and water invasion due to coning. It is considered the best approximation to the true geometry of these systems. Water intrusion to the oil reservoir is modelled numerically by attaching a concentric cylinder below the oil zone. Water saturation in the cylinder is equal to one. The radius of the aquifer entered in the model is significantly larger than the radius of the reservoir (infinite aquifer).

3. DIMENSIONAL ANALYSIS

Table 1 shows the dimensionless groups that control performance of bottom water reservoirs. A description of each one of the parameters forming the groups is presented in the nomenclature. These seven groups were obtained by [10] using Inspectional Analysis [10]. Inspectional Analysis is an extension of dimensional analysis that can be used in problems so well understood that one can write down in mathematical form all the governing laws and boundary conditions. The equations defining the problem, differential or otherwise, can then be written so that all the variables are dimensionless. Simple "inspection" then shows how these dimensionless variables are related [11].

Table 1

Dimensionless Groups Controlling Coning in Bottom-Water Systems

Number	Group Name	Symbol	Equation
1	Gravity to Viscous Forces	G_v	$\frac{kA\Delta\rho g}{\mu_o q}$
2	Well Spacing	W_{sp}	$\frac{a}{H}\sqrt{\frac{k_v}{k_h}}$
3	End-Point Mobility Ratio	M	$\frac{k_{rw}\cdot\mu_o}{k_{ro}\cdot\mu_w}$
4	Well Penetration	H_p/H	$\frac{Well\ Penetration}{Reservoir\ Thickness}$
5	Dimensionless Well Ratio	R_{wd}	$\frac{r_w}{H}\sqrt{\frac{k_v}{k_h}}$
6	Cumulative Production Parameter	R_p	$\frac{H\phi(1-S_{or}-S_{wi})}{tq/A}$
7	Capillary to Viscous Force Ratio	R_{vc}	$\frac{\sigma\cos\theta}{\Delta\rho H\sqrt{kg}}$

Only groups 1–4 are considered in this work to reduce the number of numerical experiments and because of the expected unimportance of the remaining groups. For example, the dimensionless well radius group is neglected since its possible practical range is quite small when compared to ranges for other groups. The cumulative production parameter is not considered since its value is always one. Finally, the capillary to viscous forces ratio is ignored since [10] indicated that "capillary forces do not affect the sweep efficiency of bottom water drive reservoirs over the range of conditions normally encountered in the field." In fact, it seems that [10] also ignored groups 5 to 7 in their experiments.

A large database of the reservoir parameters or properties was employed here to determine the values of the four dimensionless groups considered for analysis. Basic statistics have been obtained from the probability distributions of these properties. Monte Carlo Simulations (10,000 passes) were completed to randomly obtain probability distributions of each dimensionless group using the distributions of the individual parameters or properties. Cross plots for each possible combination of groups were made and the percentiles to be used in the design were selected within the cloud of points representing the possible reservoirs.

The P (10%), P (50%) and P (90%) of each distribution were recorded for each dimensionless group as the low, middle and high levels to be used in the design, respectively. The P (30%) and P (70%) were also recorded for the end-point mobility ratio, M, the group with the largest influence on oil bypassing. Table 2 presents the percentiles obtained for each group using Monte Carlo simulations. The range obtained for each group is quite wide and, hopefully, it represents most of possible reservoir situations.

A mixed full factorial sensitivity analysis with a total of 135 runs ($3^3 \cdot 5^1$) was designed to determine the influence of the dimensionless groups on oil bypassing. Three levels were used for all the groups except M, for which five levels were employed. The reason behind this selection will be explained in the next sections. As it can be seen in Table 35, the levels were defined by taking the 10%, 30, 50, 70 and 90% percentiles of each group.

The four dimensionless groups were validated using the numerical simulation model previously described. The idea was to vary the parameters in the dimensionless groups but holding the values of the groups themselves constant. Agreement between cases where the parameters have changed would suggest that the dimensionless groups are appropriate [12]. The validation was done using the P (50%) level of each group (see tab. 2). A total of six validation cases were run.

Table 2

Levels used for the dimensionless groups – bottom water systems

Levels	G_v	W_{sp}	M	H_p/H
Low (P10%)	0.04	0.60	0.25	0.10
Mid-Low (P30%)	–	–	0.80	–
Mid (P50%)	3.76	4.74	2.60	0.50
Mid-High (P70%)	–	–	12.14	–
High (P90%)	20.21	24.05	101.72	1.00

4. GROUPS CONTROLLING OIL BYPASSING

Relative effect of the four dimensionless groups on the by-passed oil at well abandonment were analyzed using the “Design of Experiments” option of the statistical package SAS, version 9.1.3 (2003), and the analysis of variance, ANOVA. A significance level of

5% was used in all ANOVA calculations in this study. The same abandonment condition employed for edge-water systems was used here (abandonment is defined as 98% water cut – the economic water cut limit). Figure 2 displays the contribution, expressed as percentage of the sum of squares, of the different groups to the by-passed oil.

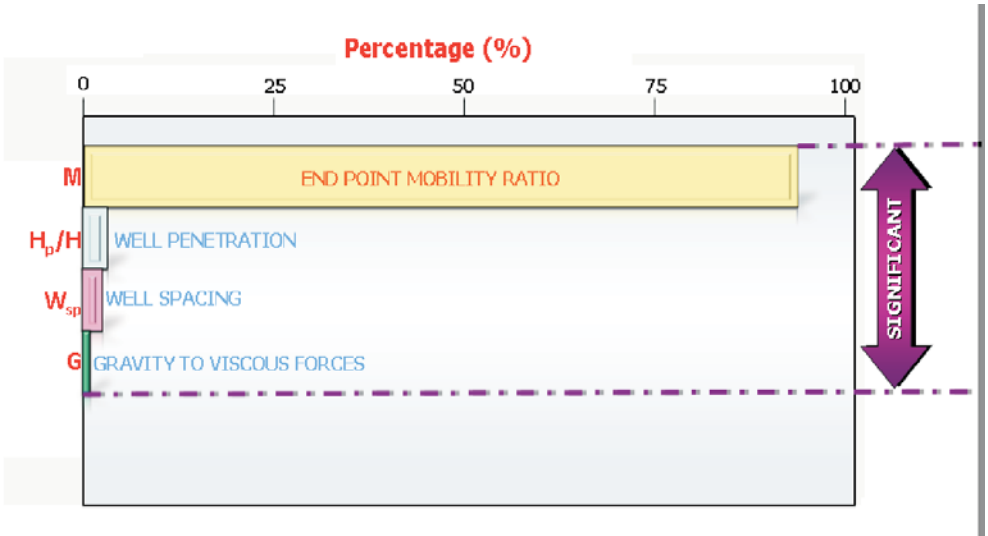

Fig. 2. Effect of dimensionless groups on oil bypassing at well abandonment

It is clear that the end-point mobility ratio, which, in this study, is a measure of the viscosity contrast between oil and water, is the main group affecting oil bypassing at abandonment conditions. Well penetration also showed to be important, which obviously suggest that short well penetrations could be used for some specific reservoir conditions to delay water invasion in bottom water systems. Overall, it was found that oil bypassing is promoted by high end-point mobility ratios, large well penetration, low gravity to viscous forces ratio (high rates) and large well spacing (large vertical to horizontal permeability ratios). It can also be seen that all the groups are statistically significant.

5. STATISTICS OF OIL BYPASSING IN TYPICAL BOTTOM WATER SYSTEMS

The amount of by[assed oil was correlated with the controlling parameters and used together with the reservoir data base to create statistics of the amount of oil that can be typically bypassed by water invasion to wells. Figure 3 shows the results in form of a plot of cumulative probability of oil bypassing at abandonment.

The figure shows that half of the reservoirs would bypass about 25% of the movable oil in place and one in five reservoirs (20% of the reservoirs) would bypass 40% or more of the oil.

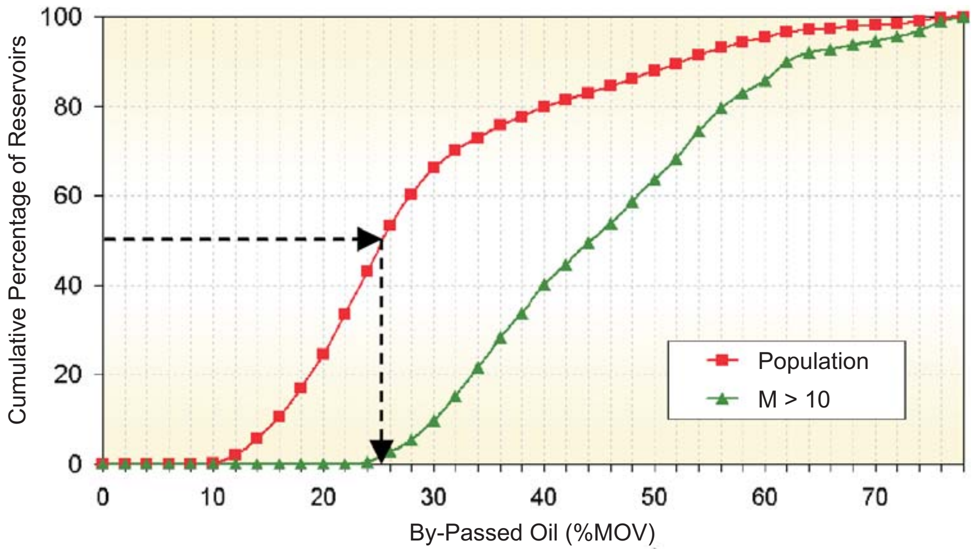

Fig. 3. Cumulative probability of oil bypassing at abandonment for bottom-water systems

It is also obvious that oil bypassing at abandonment could be very high – almost 80% for the worst case scenario. These results suggest that oil bypassing in typical bottom water reservoirs could be much more significant that in edge-water reservoirs. This is obviously because of the geometry associated to each of these systems – the initial oil water contact in typical edge water drive reservoirs is farther away than in typical bottom water systems.

In order to have an idea of the effect of the type of oil – expressed as a function of the end-point mobility ratio – on the statistics of oil bypassing, a new curve is added to Figure 3 with results for a new subgroup of reservoirs with end-point mobility ratios larger than 10 (which roughly correspond to oil viscosities larger than 20 cP). Half of this new subset of reservoirs bypasses 44% or more of the movable oil volume and one in five bypasses 56% or more. These results confirm that the problem of oil bypassing in heavy oil reservoirs could be quite critical and solutions need to be found.

6. DUAL VS. SINGLE WELL COMPLETION COMPARISON

This section shows a comparison between single (partial penetration) and dual well completions (DWS) for both newly completed and watered out wells. Two different approaches were considered to model the bottom completion in the DWS wells. The first approach involves maintaining a constant water production rate at the bottom completion during the entire production history. The approach has been used in most of the numerical simulation studies on DWS completed to date [12–17]. The second approach involves variable water production rate at the bottom completion. Variable rates are justified since the dynamics of water coning and the position of the horizontal oil water contact change with time. This new way of modeling DWS is possible due to advances in IMEX, the reservoir simulation package being used.

Table 3 shows the different cases considered in the simulations. All the case were run for G=0.03, W_{sp}=25 and M=10 and were stopped at 98% water cut at the top completion (water cut economic limit). The bottom (drainage) rate at the bottom completion was increased by a certain magnitude (given by a multiplier – as shown in the table) for each percentage point of increase in the water cut at the top completion. Maintaining water cut in the top completion at, for example, 0% would require extremely high water drainage rates, which may be impossible due to reservoir pressure constraints. This is why the water cut at the top completion must be changed in time. The magnitude of the change may obviously depend on the bottom rates that could be achieved. The maximum multiplier considered for the bottom rate was 1.025. If a higher multiplier is used, oil cut at the bottom completion will exceed 0.1% – the oil cut constraint selected for this study.

Table 3

Comparison of Single and Dual Completions

Case Name	Top Rate (BPD)	Initial Bottom Rate (BPD)	Bottom Rate Multiplier
Single Completion	360	360	–
Conventional DWS	360	360	1.0
DWS variable rate 1	360	360	1.01
DWS variable rate 2	360	360	1.02
DWS variable rate 3	360	360	1.025

Figure 4 shows oil recovery for the cases presented in table 3. The results are also summarized in table 4.

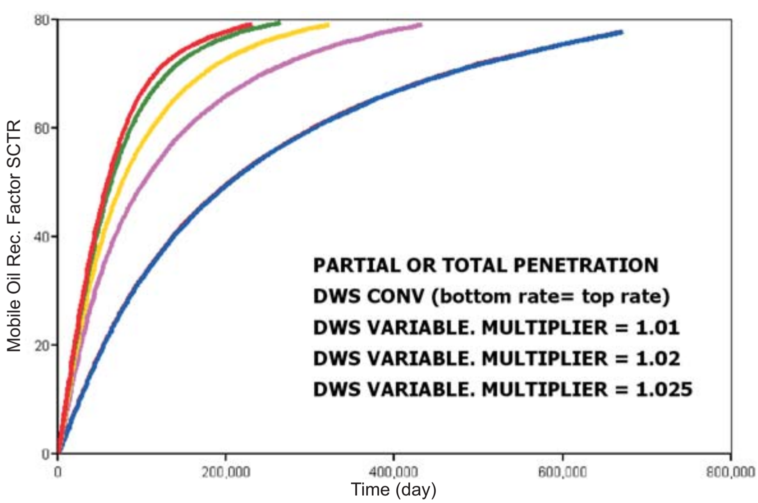

Fig. 4. Faster recoveries with dual completions

It is clear that the use of DWS results in not only higher recovery, but also in substantial acceleration of recovery. Total recovery could take almost less than a third of the time (66% shorter) than for single well completions. This may result in substantial improvements of the economics of the field. Table 4 also shows, however, that by using DWS there is a large increase on the overall cumulative water production. This is mainly because of substantial water production at the bottom completion – which is almost hydrocarbon free. In fact, cumulative water production at the top completion was found to be 2.5-fold smaller when using DWS.

One typical question on systems operated with DWS is what would the optimum time be to start the bottom completion. Our results have shown that the earlier we start the bottom completion, the faster the recovery. However, late interventions with DWS in watered out/marginal wells would always render recovery enhancement.

The results presented here show that the best completion strategy for both newly completed and watered out wells is the use of DWS, since it results in the removal or control of water coning. Additional work is required, however, to find the optimum operational parameters that will maximize recovery with DWS.

Table 4

Comparison of Single vs. Dual Completions

Case Name	Recovery at abandonment (%MOV)	% Difference-from single	% Difference on time of Recovery (days)	Cumulative Water Production (bbls)	% Difference-from single
Single Completion	77.75	–	–	2.2E+08	–
Conventional DWS	79.14	1.8	–35.3	2.9E+08	31.9
DWS variable rate 1	79.17	1.8	–51.8	3.6E+08	64.0
DWS variable rate 2	79.55	2.3	–60.5	5.5E+08	152.2
DWS variable rate 3	79.19	1.9	–65.5	6.7E+08	206.0

7. CONCLUSIONS

The main mechanisms leading to oil bypassing by water invasion in bottom water reservoirs is water coning. The effect can be minimized if production is kept below the critical rates. However, the needed critical rates are usually too low to be economical.

It was found that oil bypassing for typical bottom-water reservoirs could be significant. Half of typical bottom water reservoirs may exhibit bypassing of about 25% of the movable oil in place and one in five reservoirs (20% of the reservoirs) would have 40 or more percent of the oil bypassed.

The problem of oil bypassing in heavy oil reservoirs (mobility ratio is larger than 10) could be still more serious. The results show that half of these reservoirs may exhibit more than 44% bypassed oil while 20% reservoirs – more than 56%.

The results show that oil bypassing is promoted by high end-point mobility ratios, large well penetration, low gravity to viscous forces ratio (high rates) and large well spacing (large vertical to horizontal permeability ratios).

A comparison of single (partial penetration) and dual well completions (DWS) demonstrates advantage of DWS over conventional completion. It shows that the use of DWS could not only give higher recovery, but also in substantial acceleration of the recovery. In our simulations, recovery time with DWS was less than on-third of that for the single well completions (66% time savings). This may result in substantial improvements of the economics of the field.

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