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AN IMPROVED METHOD FOR ESTIMATING OIL RESERVES IN OIL-WATER TRANSITION ZONES

John R. Fanchi,* Richard L. Christiansen,* and Michael J. Heymans**
*Colorado School of Mines
**Geological Consultant

Abstract

The amount of recoverable oil in an oil-water transition zone depends on the distribution of oil saturation as a function of depth, and the relationship between initial oil saturation in the transition zone (S_{oitz}) and residual oil saturation in the transition zone (S_{ortz}). Traditionally, it is assumed that S_{ortz} is the same as the residual oil saturation in the oil column (S_{or}) above the transition zone. However, data in the literature show that residual oil saturation depends on initial oil saturation. So, residual oil saturation in the transition zone (S_{ortz}) should be a function of initial oil saturation in the transition zone (S_{oitz}). The relationship between S_{ortz} and S_{oitz} is referred to as a trapped oil relationship.

The purpose of this paper is to show recent experimental corroboration of the trapped oil relationship and to demonstrate the impact of the trapped oil relationship on reserves determination in oil-water transition zones. Details of the experimental work may be found in a companion paper (Christiansen et al., 1999), which discusses in depth the appropriate rock-fluid properties for characterizing transition zones. In this paper, the effect of the trapped oil relationship on reserves determination is shown in two ways: first, with an analytical model that shows the maximum possible incremental benefit of including the trapped oil relationship; and second, with an extended black oil simulation that incorporates the effects of relative permeabilities on reserves determination.

Introduction

Transition zones may vary in thickness from a few feet to a few thousand feet (Bradley, 1992). The size of the transition zone affects estimates of original hydrocarbons in place and the distribution of recoverable reserves. It is important to accurately characterize transition zones because of their potentially large effect on reservoir economics. In one example from the literature (Heymans, 1997), a 90 foot thick transition zone, in an edge-water drive reservoir with nearly a 1000 foot oil column, contributed more than 30% of the estimated original oil in place. Rigorous volumetrics and material balance calculations were within 2% agreement. In other words, the volume of hydrocarbons in a seemingly relatively thin transition zone that formed a ring around the example reservoir with edge-water drive had a significant consequence on original oil in place estimates.

An oil-water transition zone is generally described from the perspective of oil recovery as a zone in which both oil and water are produced. The top of a transition zone in a reservoir is the elevation at which water-free oil can be produced. It corresponds to the depth at which mobile water first appears. The bottom of an oil-water transition zone is the shallowest depth at which oil-free water is produced. Initial oil saturation at this depth is equal to residual oil saturation. Additional oil is not recoverable from waterflooding once the residual oil saturation to waterflooding is attained. For a more detailed discussion with graphs of conventional methods used for determining hydrocarbon recovery from a transition zone, see Christiansen et al. (1999).

Data in the literature show that residual oil saturation in the transition zone (S_{ortz}) is a function of initial oil saturation in the transition zone (S_{oitz}). The relationship between S_{ortz} and S_{oitz} is referred to as a trapped oil relationship and is illustrated in Figure 1 using a trapped gas relationship from Pickell et al. (1966). (See also Schowalter and Hess, 1982.) Trapped oil relationships can be measured in experiments with partial saturation of a sample with oil. However, such measurements of trapped oil saturations and the associated oil-water relative permeabilities are rarely reported in the literature.

Hysteresis effects provide a significant obstacle to measurement of trapped oil relationships. An experiment must be carefully designed and operated to avoid flow reversals that would complicate the interpretation of the results. Such reversals could be detected if saturation profiles in a rock sample are monitored throughout any experiments. These difficulties are considered further by Christiansen et al. (1999).

In this paper, we briefly describe the procedure and the results of recent experiments for measuring the trapped oil relationship for water-wet media as reported in detail by Christiansen et al.(1999). (Results for oil-wet media are not yet available.) Then, the effect of the trapped oil relationship on estimates of oil reserves is demonstrated using a simple analytical method and a numerical simulator. The analytical method provides a formula for estimating oil reserves in an oil-water transition zone. A numerical simulation example illustrates a relatively arduous procedure for including the trapped oil relationship in existing simulators.

Experimental Measurement of the Trapped Oil Relationship

In the discussion below, first, results and methods of previous experimental efforts are reviewed. Then, the apparatus and procedures for our tests are briefly described. Finally, a summary of results of the tests is given. For details of the experiments, see Christiansen et al. (1999).

Previous Measurements. Although there are many papers on trapped gas relationships, the literature on measurements of trapped oil relationships is sparse (see Morrow, 1987). Indeed, the only paper that reports measurements of trapped oil relationships is that of Pickell et al. (1966). Pickell et al. used porous-plate methods to saturate their sandstone samples to initial oil saturation; then, the samples were waterflooded to residual oil saturation. This method is satisfactory, yet one should be concerned that the initial saturation procedure could impart a combination of drainage and imbibition cycles on portions of the rock sample. As mentioned above, local flow reversals within the sample complicate the interpretation of the experiment.

Measurements of trapped gas saturation have been reported by many (Pickell et al., 1966; Land, 1968; Keelan and Pugh, 1973; Yuan and Swanson, 1989). The trapped gas relationship could be a good estimate of the trapped oil relationship for a rock sample, particularly if the sample is strongly water wet. Land (1968) shows six trapped gas relationships, taken from previous literature. These relationships were obtained from displacements with oil, water, and gas through rock samples.

Pickell et al. (1966) demonstrated a simpler method for measuring the trapped gas relationship, involving evaporation and re-saturation with a hydrocarbon liquid. Several groups have used that method since. Again, flow reversals may complicate interpretation of these experiments. One can easily imagine that evaporation could dry completely the external portion of the rock, while the internal rock is still saturated with liquid. So, careful experimental design and operation is needed to obtain trapped gas relationships.

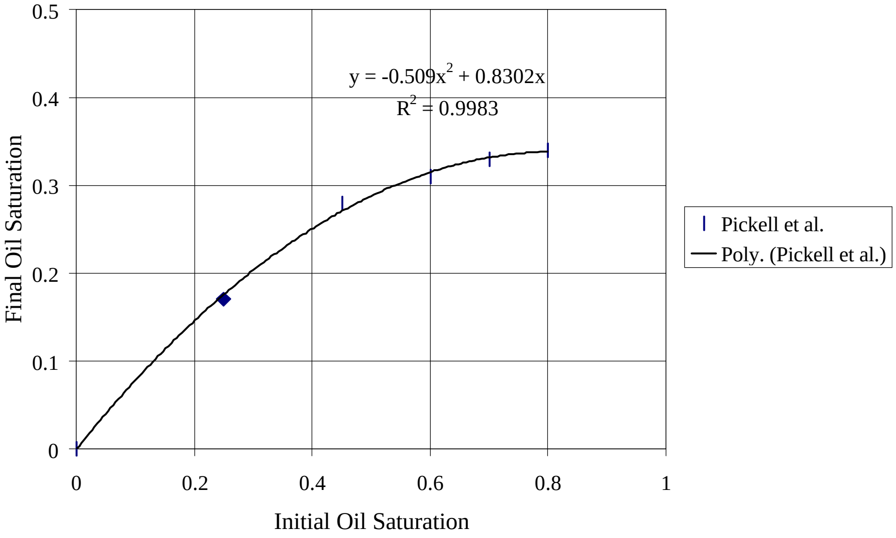

Figure 1. A trapped oil relationship, as estimated from a trapped gas relationship in Figure 7 of Pickell et al. (1966).

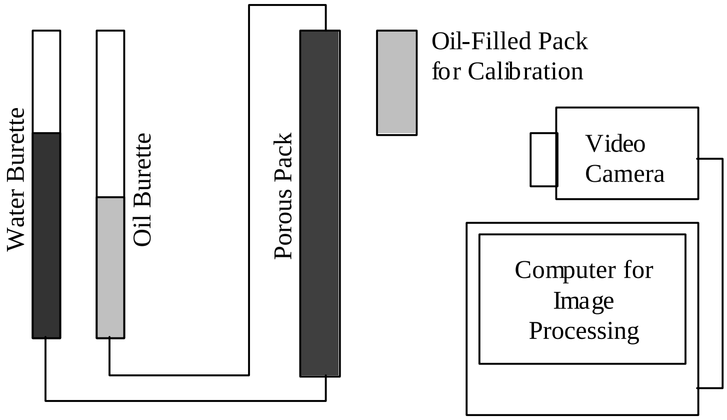

Figure 2. Schematic of apparatus for saturation profile measurement with unconsolidated media.

Experimental Apparatus and Procedures. The apparatus for the experiments consists of an unconsolidated pack connected to two burettes containing nonane and water, a video camera, and a computer for capturing video images. The apparatus is sketched in Figure 2.

The unconsolidated media consisted of glass beads (70-100 mesh, with particle diameters from 0.15 to 0.21 mm; porosity = 39%; permeability = 24 darcies), and sand (20-40 mesh, with particle diameters from 0.42 to 0.84 mm; porosity = 32%; permeability = 150 darcies). The media was packed into a 48.3-cm-long acrylic tube (1.27-cm OD x 0.97-cm ID. The bottom of the pack was connected with flexible tubing to the burette containing water; the top was connected to the nonane burette. The liquids were dyed to enhance visibility. Video images of displacements in the vertical pack were captured and processed with NIH Image software. With this software, sequential images could be compared to determine if a stable profile of gray levels had been obtained. Gray levels from the video images were converted to saturations using a simple correlation.

At the start of an experiment, the packed tube was saturated with water and connected to the water and nonane burettes. Then, either the water burette was lowered or the oil burette was raised to force oil slowly into the top of the porous medium packed in the tube. After moving the burettes, some time was allowed to obtain a stable gray level profile as the oil-water saturation profile evolved. Stabilization was determined from the oil and water levels in the burette and from video images of the packed tube. When the height of the oil invasion zone was at least 75% of the height of the packed tube, the direction of oil movement was reversed by forcing water into the bottom of the packed tube.

Results. Trapped oil relationships were obtained by cross-plotting saturation profiles for upward movement of the oil-water contact against saturation profiles for downward movement. Typical results are shown in Figures 3 and 4. Lines are included in both figures to accentuate the trends in the data. These cross-plots show many of the expected characteristics of a trapped oil relationship.

With the video approach, one is cursed with an enormous quantity of gray-level data. (Each gray-level profile consists of about 500 points.) As the size of a video pixel (about 1 mm) is not much larger than the grain size, especially for the 20-40 sand, the gray level of several adjacent pixels should be averaged to get local saturation. Pixel gray levels were averaged in the horizontal direction, but not in the vertical direction. Much of the scatter in Figures 3 and 4 probably results from the absence of vertical averaging.

When obtained from local saturation measurements, the shape of the trapped oil relationship is known within the uncertainty of the saturation measurements. (The relationship is especially difficult to specify as oil saturation approaches zero.) The accuracy of the saturation measurements is not well known; that is, saturations estimated using the gray-level correlation of the video approach have not been compared directly to saturations measured by another approach (other than at the endpoints of the correlation). However, material balances calculated from the saturation profiles described in Christiansen et al. (1999) show agreement within 5% for many experiments and within 20% for other experiments. Certainly, additional effort is needed to improve the quality of the data with the video approach.

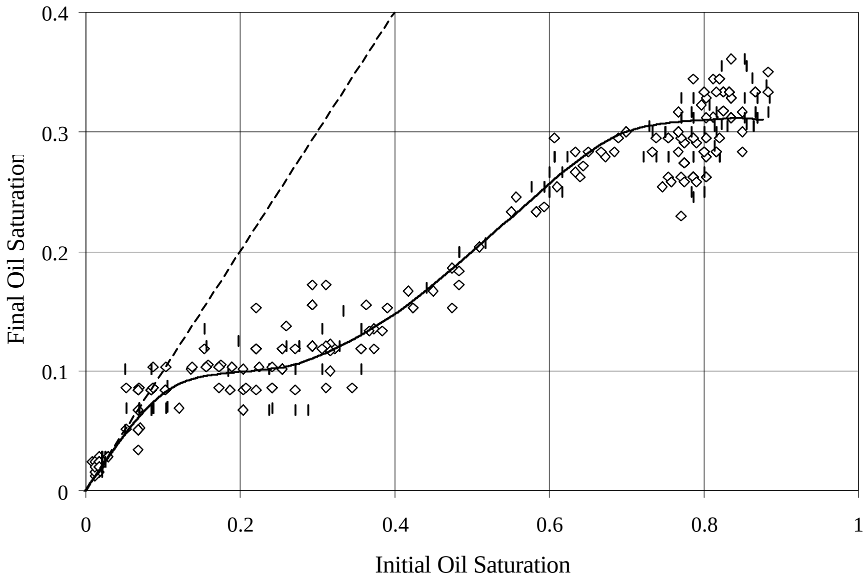

Figure 3. Trapped oil relationship for 70-100 mesh glass beads from saturation profile measurements. The line is shown just to highlight the trend. A "45 Degree" line is also shown.

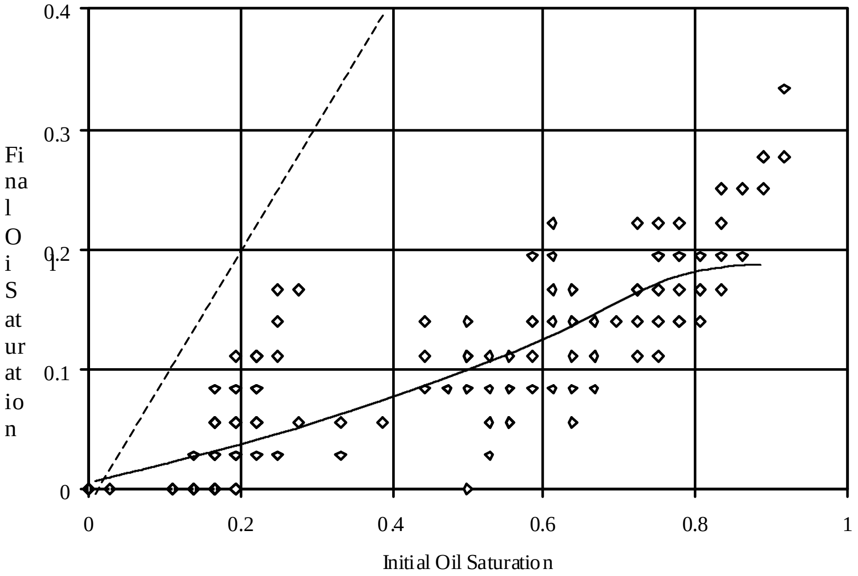

Figure 4. Trapped oil relationship for 20-40 mesh sand from saturation profile measurements. The line is shown just to highlight the trend. A "45 Degree" line is also shown.

Analytical Method for Estimating Oil Reserves

Trapped oil core test measurements show that an empirical relationship exists between an initial oil saturation (S_{oi}) and the associated residual oil saturation (S_{or}). Recoverable oil saturation is the difference between S_{oi} and the associated S_{or}. When trapped oil measurements are related to an oil saturation profile as a function of height, the relationship shows that S_{or} decreases with depth within a transition zone. The depth variation of S_{oi} and S_{or} results in hydrocarbon recovery being greater at the top of a transition zone and decreasing with depth and S_{oi}.

The conventional method for estimating oil reserves in a transition zone is based on the assumption that residual oil saturation is constant throughout the transition zone. Including the trapped oil relationship in calculations of oil reserves is a new method of analysis. The analytical method described here provides more accurate reserve estimates than procedures that neglect the trapped oil relationship. The effect of the analytical method is illustrated below with a specific example.

Figure 5 shows two possible initial water saturation profiles as a function of depth. The depth is measured relative to the top of the transition zone. Combining the initial water saturation profiles of Figure 5 with residual oil relationships gives enough information to estimate the effect of the trapped oil relationship on the estimate of oil reserves in the transition zone. The fractional increase in estimated oil reserves is as follows:

$$\frac{dN}{N_c} = \frac{N_v - N_c}{N_c}$$

where N_c is mobile oil calculated using the conventional assumption that S_{or} is constant in the transition zone, and N_v is mobile oil calculated using the assumption that S_{or} varies with depth in the transition zone. Our task is to calculate $\delta N/N_c$ by first calculating N_c and N_v.

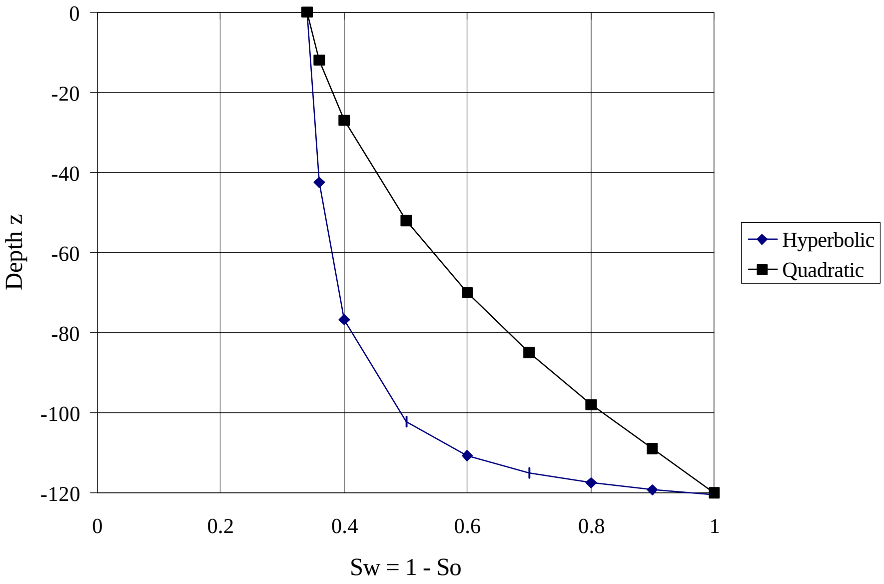

Figure 5. Two possible saturation profiles in a transition zone.

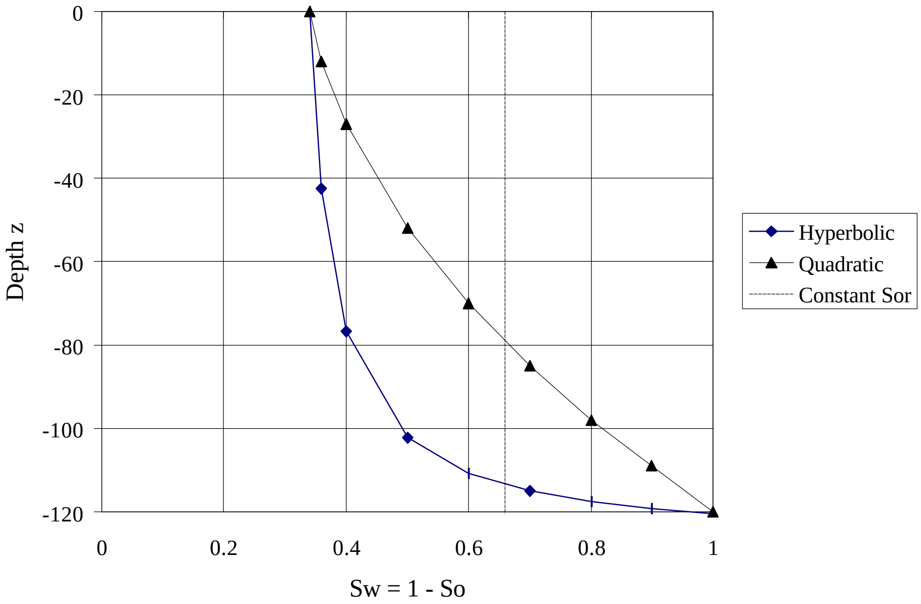

Figure 6. Saturation profiles with constant S_{or}.

The saturation profiles are shown in Figure 6 with constant S_{or}. The average mobile oil saturation $\langle S_{om} \rangle_c$ in the case with constant S_{or} is

$$\langle S_{om} \rangle_c = \langle S_{oi} \rangle_c - S_{or}$$

where $\langle S_{oi} \rangle_c$ is the average initial oil saturation

$$\langle S_{oi} \rangle_c = \int_0^{z_c} S_{oi} dz \bigg/ \int_0^{z_c} dz$$

Transition zone thickness z_c is measured from the top of the transition zone to the point of intersection of the initial oil saturation curve ($S_{oi} = 1 - S_{wi}$) and S_{or}. The mobile oil in the transition zone assuming constant S_{or} is

$$N_c = jAz_c \left[\langle S_{oi} \rangle_c - S_{or} \right]$$

where the transition zone pore volume is the product of porosity φ, cross-sectional area A and thickness z_c.

The saturation profiles with variable S_{or} are shown in Figures 7 and 8 where Figure 1 has been used to provide a trapped oil relationship. The average mobile oil saturation $\left\langle S_{om} \right\rangle_v$ in the case with variable S_{or} is

$$\left\langle S_{om} \right\rangle_v = \left\langle S_{oi} \right\rangle_v - \left\langle S_{or} \right\rangle_v$$

where $\left\langle S_{oi} \right\rangle_v$ is the average initial oil saturation

$$\left\langle S_{oi} \right\rangle_v = \int_0^{z_v} S_{oi} dz \Bigg/ \int_0^{z_v} dz$$

The transition zone thickness z_v is measured from the top of the transition zone to the point of intersection of the initial oil saturation curve ($S_{oi} = 1 - S_{wi}$) and the variable S_{or} curve. In this case, the intersection is at $S_{or} = 0$ for the trapped oil relationship given in Figure 1. The mobile oil in the transition zone assuming variable S_{or} is

$$N_v = j A z_v \left[\left\langle S_{oi} \right\rangle_v - \left\langle S_{or} \right\rangle_v \right]$$

where the transition zone pore volume is the product of porosity φ, cross-sectional area A and thickness z_v.

The fractional increase in reserves for each saturation profile is given by the expression

$$\frac{dN}{N_c} = \frac{\left[\left\langle S_{oi} \right\rangle_v - \left\langle S_{or} \right\rangle_v \right] z_v}{\left[\left\langle S_{oi} \right\rangle_c - S_{or} \right] z_c} - 1$$

Results for the two saturation profiles are presented in Table 1. The “hyperbolic” saturation profile had a relatively small increase of approximately 11%, while the “quadratic” saturation profile had almost a 37% increase.

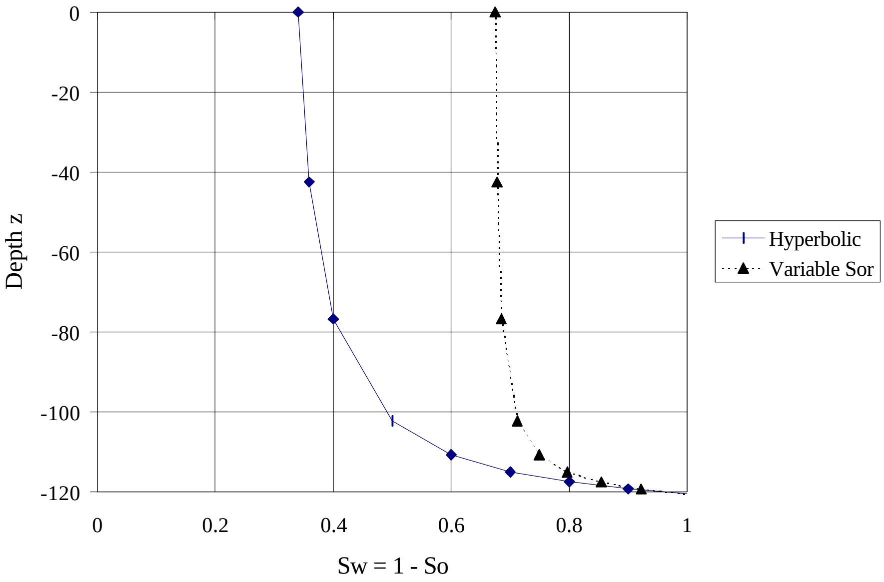

Figure 7. Hyperbolic saturation profile with variable S_{or}.

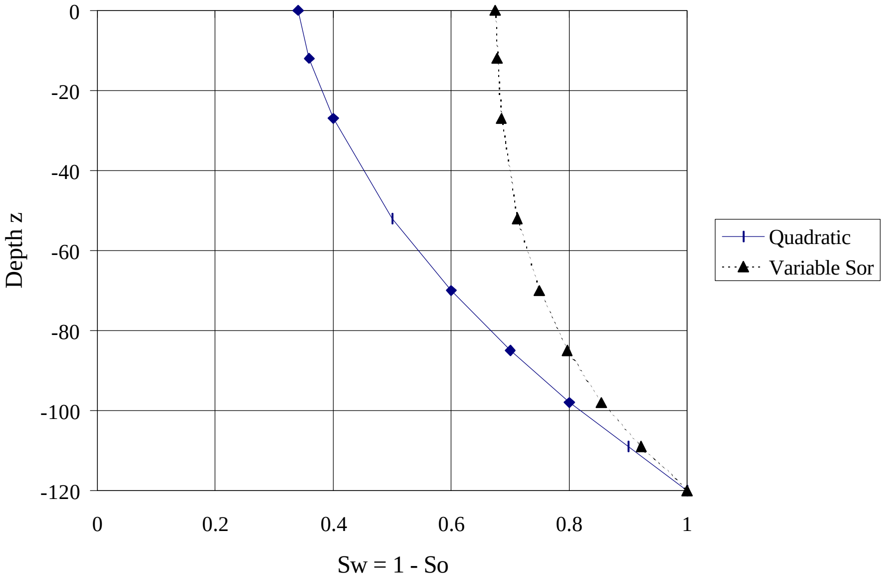

Figure 8. Quadratic saturation profile with Variable S_{or}.

Table 1. Fraction Increase in Estimated Reserves for Two Saturation Profiles.

Variable	Hyperbolic Case	Quadratic Case
z_c	113.6 ft	80 ft
z_v	120 ft	120 ft
$\left\langle S_{oi} \right\rangle_c$	0.695	0.526
S_{or}	0.340	0.340
$\left\langle S_{oi} \right\rangle_v$	0.697	0.326
$\left\langle S_{or} \right\rangle_v$	0.326	0.226
$\delta N/N_c$	10.7 %	36.8 %

Transition Zone Volumetrics Using a Numerical Simulator

Numerical simulators are powerful tools for enhancing reservoir management decisions. Typically, capillary pressure and relative permeability core test measurements with constant residual oil saturation are used in reservoir model studies. However, proper modeling of the trapped oil relationship requires that the simulator account for depth dependent residual oil saturation. This effect can be achieved in existing simulators, but the process is arduous. In particular, a layer cake grid consisting of planes of grid blocks is used to represent the reservoir. Vertical variations in reservoir properties such as porosity and permeability can still be entered. Each layer is treated as a Rock Region; i.e. each layer is assigned its own set of relative permeability and capillary pressure curves. The model can then be initialized.

Relative permeability curves should account for the variation in residual oil saturation. Although the trend of relative permeabilities for varying residual oil saturation is unknown, the relative permeabilities for this example were approximated by normalizing the measured curves and then denormalizing the curves for the saturation end points assigned to each Rock Region.

To verify this procedure, a vertical column model of the transition zone at the base of an undersaturated oil reservoir was run using an extended black oil simulator. A production well was placed at the top of the column and a water injection well was assigned to the lowermost grid block. Initial saturations were based on the quadratic saturation profile presented in Figures 4 and 5. The original oil in place in this model was 3.01 MMSTB. The model with a constant S_{or} produced 0.90 MMSTB oil before a limiting water-oil ratio of 5 STB water/STB oil was reached. The corresponding model with a variable S_{or} produced 1.24 MMSTB oil before reaching the WOR limit. The fractional increase in oil recovery was approximately 38%, which is in good agreement with the value predicted in the previous section.

It is possible to model the trapped oil relationship in existing simulators, but the process is cumbersome. A better procedure would be to modify existing simulators to account for the variation of residual oil saturation with depth that is a consequence of the trapped oil relationship in transition zones.

Conclusions

From the experiments described above and from those reported in the literature, the following conclusions are offered:

1. Residual oil saturation depends on initial oil saturation. The dependence is expressed in trapped oil relationships. Recent experimental results corroborate measurements reported in the literature.
2. Estimates of reserves for fields with transition zones can be significantly increased by the inclusion of mobile oil at low initial saturations as contained in a trapped oil relationship.
3. To estimate the reserves available in the transition zone, one must incorporate the total reservoir volume of the transition zone. For example, in a reservoir with an edge-water drive, significant reserves may be available because of the large oil volume near the edge of the reservoir.

The above conclusions depend on a relatively small experimental data base. More work is needed to address several remaining issues: the effect of wettability on the trapping relationship, and relative permeabilities for oil and water in the transition zone.

In addition, the following conclusions have been demonstrated:

4. The effect of varying residual oil saturation on transition zone reserves can be estimated with an analytical approach.
5. Improvements in existing simulators are needed to facilitate the inclusion of a trapped oil relationship and the attendant relative permeability relationships in model initialization and execution.

Acknowledgements

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