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RESERVOIR ENGINEERING IMPLICATIONS OF CAPILLARY PRESSURE AND RELATIVE PERMEABILITY HYSTERESIS

by

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ABSTRACT

Hysteresis was observed in centrifuge and porous plate capillary pressure measurements and in steady-state and unsteady-state relative permeability measurements. The hysteresis was significant enough to affect reservoir engineering calculations. Two types of hysteresis were seen: flooding phase dependent and cycle dependent. Capillary pressure curves exhibited considerable cycle dependent hysteresis, especially the oilflood curve. Because of cycle dependent hysteresis, reservoir engineers using oilflood capillary pressure data to specify water saturations in the reservoir should use first-cycle oilflood data. Similarly, reservoir engineers simulating waterfloods should use relative permeabilities measured on a first-cycle waterflood. In tertiary enhanced oil recovery processes residual oil is mobilized into an oil bank which then displaces water in the reservoir. Second-cycle oilflood relative permeabilities are thus required for enhanced oil recovery simulation.

Cycle dependent hysteresis has significant implications for native-state (as-received) core analysis. For waterflood simulation, relative permeability and capillary pressure data should be from a first-cycle waterflood. However, cores cut with a water-based mud, or cores from a waterflooded reservoir, will already have undergone a first-cycle waterflood prior to reaching the laboratory. Subsequent measurements are necessarily made on the second cycle. First-cycle waterflood measurements can, however, be made on restored-state core.

INTRODUCTION

Capillary pressure and relative permeability data are very important to reservoir engineering. Capillary pressure data are used in fluid flow calculations, and can be converted to height above the oil-water contact, thus describing the water saturation distribution in the reservoir. The water saturation distribution is used to initialize the reservoir simulator. Relative permeability data are used in fluid flow calculations. The importance of wettability and test conditions when measuring these properties have been well documented (Anderson 1987a, 1987b). Equally important, however, is the necessity of honoring saturation history.

Both capillary pressure and relative permeability data exhibit a non-repeatability dependent on saturation history. This non-repeatability is commonly referred to as hysteresis. (The phenomenon is not true hysteresis, in that the saturation history effect is not reversible.) As described below, numerous papers have indicated the presence of hysteresis in capillary pressure and relative permeability measurements. Other papers have provided evidence of hysteresis in the reservoir and have shown the necessity of including hysteresis in reservoir simulation history matching (Patel, et al., 1985; Denoyelle and Lemonnier, 1987; Moore and Clark, 1988).

Two types of hysteresis are seen: flooding phase dependent and cycle dependent. Flooding phase dependent hysteresis means waterflood results were different than oilflood results. Cycle dependent hysteresis means results were different for successive floods with the same phase. Capillary pressure and relative permeability measurements exhibit both types of hysteresis. Examples from laboratory data are presented to show flooding phase and cycle dependent hysteresis. After establishing the reality of hysteresis, the implications of hysteresis for data acquisition and reservoir engineering are discussed. The focus of this paper is oil/brine systems, however, the existence and implications of hysteresis would also be significant for gas/oil systems.

The terms imbibition and drainage are often used in the literature to describe flooding processes. However, these terms can be misleading, since the wetting preference of the system also needs to be indicated. Imbibition is an increase in the wetting phase, for example, a waterflood of a water-wet rock or an oilflood of an oil-wet rock. Use of the term imbibition without defining wetting preference is thus ambiguous. Also in a neutrally-wet rock the term becomes meaningless. In this paper we will use the terms oilflood and waterflood to indicate the flooding phase.

CAPILLARY PRESSURE HYSTERESIS

Sanyal and co-workers (1973) and Szabo (1974) published capillary pressure data which exhibited hysteresis. Other examples of capillary pressure hysteresis come from Longeron et al. (1986), Batycky et al. (1981), Sinnokrot et al. (1971), and Evrenos and Comer (1969). Figures 1 and 2 present examples of flooding phase and cycle dependent capillary pressure hysteresis we have measured. These curves were measured on Berea sandstone by the centrifuge technique using a refined mineral oil and a synthetic brine as fluids. Subsequently, the measurements were duplicated using the porous plate technique.

Flooding Phase Dependent Hysteresis

The first-cycle oilflood capillary pressure curve in Figure 1 starts at 100% water saturation, and proceeds to irreducible water saturation (S_{wi}). A first-cycle oilflood capillary pressure curve simulates the capillary pressure gradient established when oil initially migrated into the water saturated reservoir. The first-cycle waterflood capillary pressure curve starts at S_{wi} and proceeds to residual oil saturation (S_{or}). This curve simulates the capillary pressure present when the reservoir is being waterflooded or under natural waterdrive. The capillary pressure curves were different during the oilflood than for the waterflood and this difference is designated as flooding phase dependent hysteresis. When measuring first-cycle oilflood capillary pressure data, it is necessary to not only establish capillary pressure equilibrium at each pressure step but also to allow wettability equilibrium to occur.

Sanyal et al. (1973) presented flooding phase dependent hysteresis for oil/water systems for capillary pressures measured using a membrane technique. Szabo (1974) presented centrifuge capillary pressure data which exhibited flooding phase dependent hysteresis. Longeron et al. (1986) presented porous plate capillary pressure data which also exhibited flooding phase dependent hysteresis.

Cycle Dependent Hysteresis

Figure 2 shows that the capillary pressure curves were different during the first-cycle oilflood than during the second-cycle oilflood and this difference is designated as cycle dependent hysteresis. Longeron et al. (1986), Batycky et al. (1981) and Evrenos and Comer (1969) also give examples of cycle dependent capillary pressure hysteresis. The measurements of Longeron et al. (1986) were carried out using a porous plate technique.

RELATIVE PERMEABILITY HYSTERESIS

Examples of relative permeability hysteresis to be found in the literature include: Torabzadeh and Handy (1984), Fulcher et al. (1983), Amaefule and Handy (1982), Braun and Blackwell (1981), Chierici (1981), Batycky et al. (1981), Sinnokrot et al. (1971), Land (1971), and Evrenos and Comer (1969). Figures 3 and 4 are examples of relative permeability hysteresis we have measured. These measurements were made on a synthetic core, composed of uniform beads (EP brand porous structure), using a refined mineral oil and distilled water. This synthetic core is fairly oil-wet in nature. The hysteresis we have observed has been both for steady-state and unsteady-state measurement techniques. The hysteresis was also observed in both ambient condition and reservoir condition tests. We have observed hysteresis in relative permeability measurements for carbonates and sandstones from the Middle East, West Texas, Wyoming and New Mexico.

Flooding Phase Dependent Hysteresis

Relative permeability curves are different during the oilflood than during the waterflood. This difference is termed flooding phase dependent hysteresis and can be seen in Figure 3 by the difference between the solid and dashed curves. Our data is consistent with the literature data in that greater hysteresis is seen in the relative permeability of the non-wetting phase. In Figure 3 the larger difference in curves between the oilflood and waterflood is seen in the water relative permeability curves for this oil-wet rock. Torabzadeh and Handy (1984), Fulcher et al. (1983), Amaefule and Handy, (1982); Braun and Blackwell (1981), Chierici (1981), Batycky et al. (1981), Sinnokrot et al. (1971), and Evrenos and Comer (1969) all give examples of flooding phase dependent hysteresis for relative permeabilities. The data reported by Braun and Blackwell (1981), Amaefule and Handy (1982) and Fulcher et al. (1983) were measured using the steady-state technique.

Cycle Dependent Hysteresis

Relative permeability curves are different for a first-cycle waterflood than for a second-cycle waterflood. This difference is termed cycle dependent hysteresis, and can be seen by the difference between the dashed and solid curves in Figure 4. The difference in S_{wi} values between the first and second-cycle oilfloods also indicates cycle dependent hysteresis for the oilfloods. The oilfloods were performed at the same flow rate with equivalent pore volumes injected and yet S_{wi} for the first-cycle is 30 saturation percent less than S_{wi} for the second-cycle oilflood. Torabzadeh and Handy (1984) give examples of cycle dependent hysteresis for oilflood curves. Evrenos and Comer (1969) give examples of cycle dependent hysteresis for floods with both the wetting and non-wetting phases.

IMPLICATIONS OF HYSTERESIS

The existence of hysteresis has been reported on numerous occasions in the literature. Flooding phase dependent hysteresis has been investigated and reported more extensively than cycle dependent hysteresis and our data verifies the existence of both types. Given the fact of hysteresis, then there are significant implications for the acquisition and use of special core analysis data which are outlined in the following sections.

Capillary Pressure - Transition Zone Saturations in the Reservoir

Capillary pressure data can be used to estimate S_{wi} and transition zone saturations in a reservoir. The capillary pressure is converted to height above the oil-water contact to give the saturation distribution (Slider 1983). In the generally accepted theory of petroleum migration, reservoir rock originally saturated only with water is invaded by petroleum (Tissot and Welte, 1978). The water saturation distribution in the reservoir is then established by capillary pressure during this first-cycle oilflood. Figure 2 shows the significant difference for S_{wi} values and water saturation distributions for first and second-cycle oilfloods. Using the second cycle curve, one would overestimate the oil in the transition zone by 100 percent and underestimate the original oil-in-place above the transition zone by about 11 percent.

Relative Permeability - Waterflood

Waterflood relative permeability data is used in a reservoir simulation model to predict waterflood performance. When a reservoir is waterflooded that waterflood is on a first cycle. Thus, reservoir engineers simulating waterfloods should use first-cycle waterflood relative permeability data. Comparing the first and second-cycle waterflood curves in Figure 4, we see that significant errors would occur in reservoir simulation estimates if the second-cycle waterflood relative permeability curves were used. The error that would result would depend on the magnitude of the cycle dependent hysteresis.

Relative Permeability - EOR (Oilflood)

During a tertiary enhanced oil recovery (EOR) process residual oil is mobilized into an oil bank, which then displaces water ahead of it. The sequence is an EOR fluid displacing an oil bank and an oil bank displacing water. The oil bank displacing water is actually a second-cycle oilflood. Therefore, it is important when conducting EOR simulation to use second-cycle oilflood relative permeability data. Comparing the first-cycle waterflood and second-cycle oilflood curves in Figure 3, we see the large error that would occur in the EOR simulation if the waterflood curves rather than the oilflood curves were used. The depressed water relative permeability during the oilflood actually aids the displacement efficiency of the EOR process and would also affect the injectivity of the EOR fluid.

Relative Permeability - Centrifuge Measurement

The centrifuge method has been used to obtain relative permeability data (O'Mera and Lease, 1983). The major limitation of the method is that oil relative permeabilities are measured during a waterflood and water relative permeabilities are measured during an oilflood. Because of flooding phase dependent hysteresis, the use of relative permeability curves measured with different flooding phases would result in significant errors.

Wettability

Examining Figure 4 and using Craig's rules of thumb (1971), the first-cycle waterflood curves indicate that the rock is moderately oil-wet. However, the second-cycle waterflood curves indicate that the rock is water-wet. Since these tests were run on synthetic core with bland fluids, no wettability alteration should have occurred. Use of the second-cycle curves appears to incorrectly estimate rock wettability.

Native-State Core Analysis

The cycle dependent hysteresis that we have observed has significant implications for native-state core analysis. In work that was conducted by Sharma and Wunderlich (1987) and Yan et al. (1988), the suitability of native-state core analysis was questioned because of potential rock wettability alteration by drilling fluid components. Lease crude is sometimes used as a drilling fluid to preserve native-wettability, however, even lease crude could be subject to exposure and oxidation by air, thus altering wettability. Wettability concerns aside, hysteresis should be considered when conducting native-state analyses. It is not possible to obtain first-cycle oilflood capillary pressure measurements from native-state core. In addition, it is not possible to obtain first-cycle waterflood data from native-state core if the core was:

1. Cut with a water-based mud - If the core is cut with a water-based mud, then the core will be flushed during coring by mud filtrate. Such flushing constitutes a first-cycle waterflood, and subsequent waterflood measurements are on the second cycle.

2. Cut from a waterflooded portion of a reservoir - If the core is cut from a portion of a reservoir that is being waterflooded, or under water encroachment, the core will have undergone a first-cycle waterflood prior to coring. Any laboratory measurements of waterflood data are necessarily on the second cycle.

3. Flushed with brine in the laboratory - It is a common practice in laboratories to flush core samples with brine to remove mud filtrate and gas prior to measurement. The plug is then oilflooded and finally measurements are made on a second-cycle waterflood.

When conducting native-state analyses, one should take into account cycle dependent hysteresis to avoid the errors that can result by using data from the wrong cycle in reservoir engineering calculations. Restored-state analysis allows measurement of capillary pressures and relative permeabilities on the appropriate cycle. Using bland muds and minimizing mud filtrate invasion are important even when planning restored-state analysis, because the core will be easier to clean if contamination is limited.

Saturation Exponent

We have observed hysteresis in capillary pressure and relative permeability curves. Sanyal et al. (1972) presented data to show flooding phase dependent hysteresis in saturation exponent. Longeron et al. (1986) presented results which showed flooding phase and cycle dependent hysteresis in saturation exponent measurements. Because of hysteresis, resistivity logs run in a newly discovered reservoir should be interpreted using a saturation exponent measured during a first-cycle oilflood. For logs run in a waterflooded reservoir, or in water-flushed zones, the saturation exponent should be measured during a first-cycle waterflood.

CONCLUSIONS

1. Both cycle dependent and flooding phase dependent hysteresis have been observed in capillary pressure measurements. The hysteresis was seen in both porous plate and centrifuge measurements.

2. Both cycle dependent and flooding phase dependent hysteresis have been observed in relative permeability measurements. The hysteresis was seen in both steady-state and unsteady-state measurements.

3. Cycle dependent hysteresis should be considered when using oilflood capillary pressure data to estimate transition zone fluid saturations. First-cycle oilflood data should be used.

4. Because of cycle dependent hysteresis, first-cycle waterflood relative permeability data should be used for engineering waterfloods.

5. Because of flooding phase dependent hysteresis, second-cycle oilflood relative permeability data should be used to simulate the oil bank developed during tertiary enhanced oil recovery processes.

6. Centrifuge measured relative permeability data are not consistent, since the oil and water relative permeability curves are measured with different flooding phases.

7. Wettabilities inferred from relative permeability data can be erroneous if data other than first-cycle waterflood data are used.

8. Cycle dependent hysteresis needs to be considered when conducting native-state core analysis. If cores are cut with a water-based mud, cut from a waterflooded zone, or core samples are brine flushed in the laboratory, it is not possible to obtain the necessary first-cycle waterflood data.

9. Because of hysteresis effects the saturation exponent used to interpret resistivity logs needs to be measured on the appropriate cycle and with the appropriate flooding phase.

10. Hysteresis was observed in the absence of wettability affects, thus it is likely that a cause for hysteresis is fluid distribution at the pore level.

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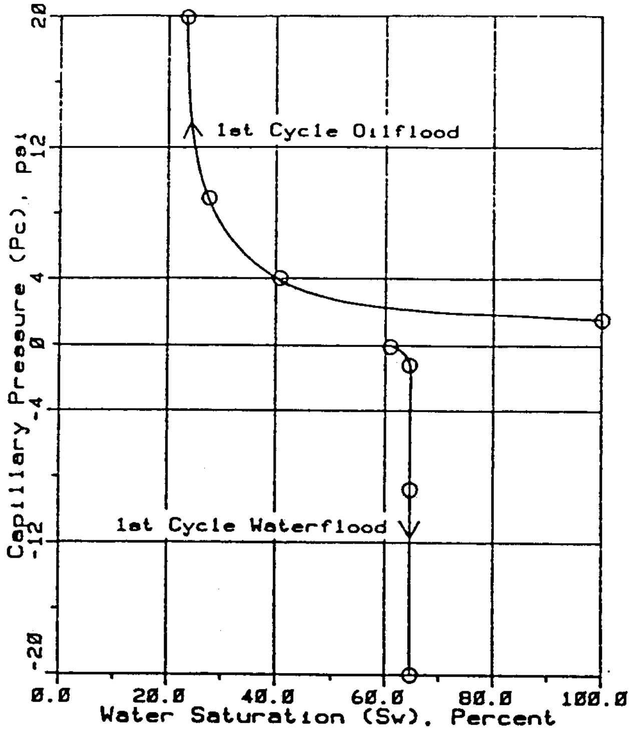

Figure 1. Flooding phase dependent capillary pressure hysteresis.

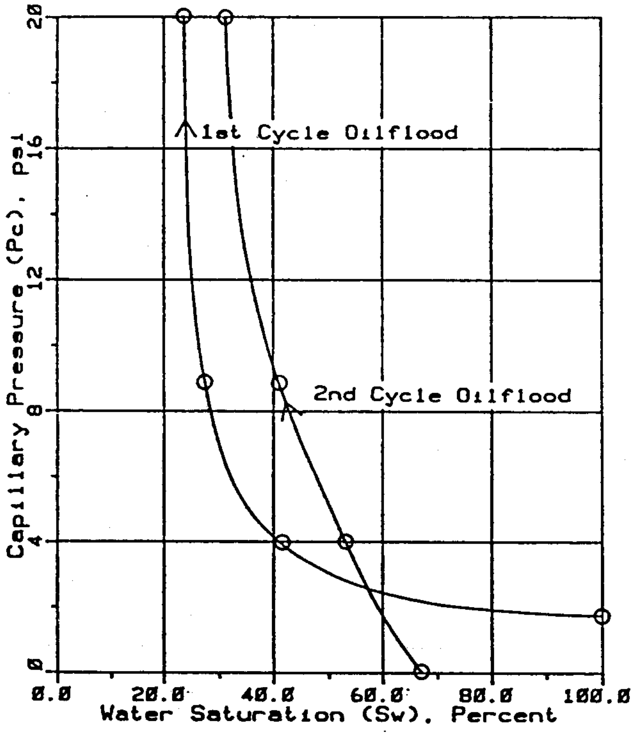

Figure 2. Cycle dependent capillary pressure hysteresis.

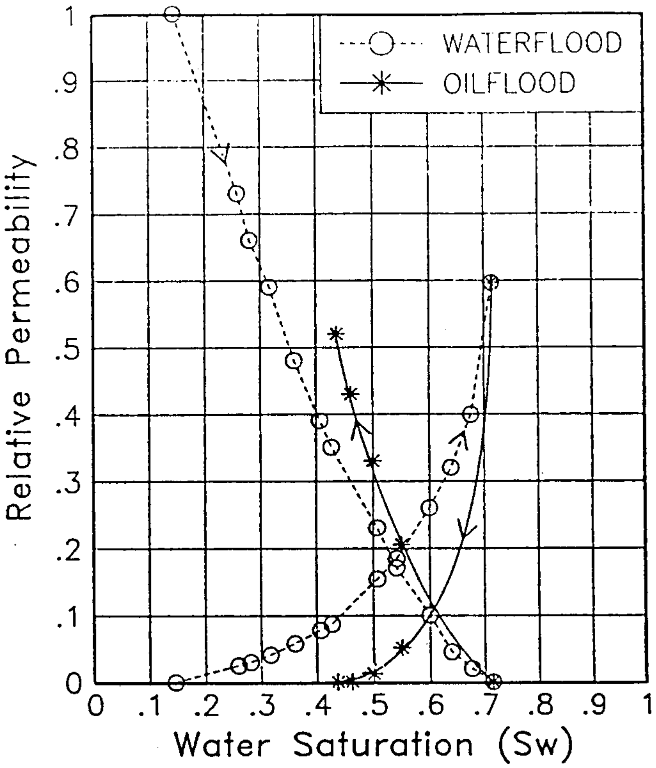

Figure 3. Flooding phase dependent relative permeability hysteresis.

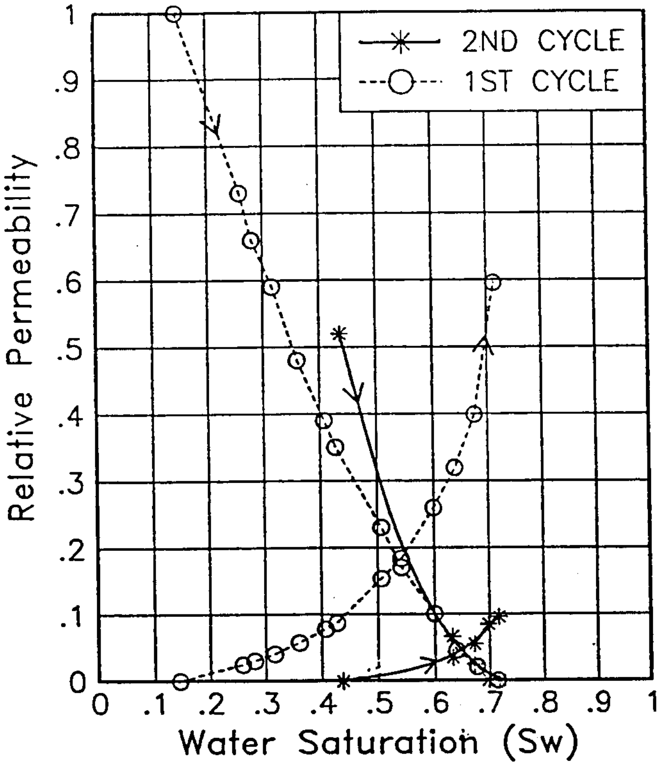

Figure 4. Cycle dependent relative permeability hysteresis.