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Evaluation of Reservoir Wettability and its Effect on Oil Recovery

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By:

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TITLE: EVALUATION OF RESERVOIR WETTABILITY AND ITS EFFECT ON OIL RECOVERY

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Objectives

This project has three main goals. The first is to achieve improved understanding of the surface and interfacial properties of crude oils and their interactions with mineral surfaces. The second goal is to apply the results of surface studies to improved predictions of oil production in laboratory experiments. Finally, we aim to use the results of this research to recommend ways to improve oil recovery by waterflooding.

In order to achieve these goals, the mechanisms of wetting alteration must be explained. We propose a methodology for studying those mechanisms on mineral surfaces, then applying the results to prediction and observation of wetting alteration in porous media. Improved understanding of the underlying mechanisms will show when and how wettability in the reservoir can be altered and under what circumstances that alteration would be beneficial in terms of increased production of oil.

Summary of Technical Progress

1. Crude Oil/Brine/Solid Interactions

In the work reported this quarter, crude oil interactions with Berea sandstone have been used to prepare cores with mixed wettability, as discussed in the following section in this report.

2. Wetting Evaluation

Dependence of relative permeability on flow rate

Permeability k_a represents a constant of proportionality between pressure drop and flow rate, as defined by Darcy's Law. It is assumed to be invariant with pressure drop, except for the extremes of high flow rates (Forchheimer effect) and low permeability (Klinkenberg effect), neither of which should have an important impact in this study.

Relative permeabilities that describe the flow of one fluid in the presence of another are also considered to be constant with changing flow rates and pressures, below some critical value at which residual phase begins to be mobilized. Relative permeabilities have often been measured in laboratory corefloods performed at rates well in excess of those typical in an oil reservoir, with the aim of minimizing the contribution of capillary forces. Implicit in these tests is the assumption that relative permeabilities would not be affected by changes in flow rate. Results presented in this report show that under the flow-rate conditions commonly used in laboratory core experiments, this assumption is valid only for strongly water-wet conditions.

Although rate effects may influence relative permeability at any saturation, the best defined conditions exist when only one of the phases is flowing. Thus in this study, we focus on the end-point permeability to water in the presence of a residual saturation of oil. At each flow rate, the test continued until no further change in pressure was detected.

Strongly water-wet conditions

Outcrop Berea sandstone is strongly water-wet (Amott index to water $I_w = 1$, Amott index to oil $I_o = 0$[1]). **Figure 1** shows that over a wide range of flow rates the relationship between flow rate and pressure drop is constant for water flowing in the presence of residual Soltrol-130, a refined mineral oil. There is no hysteresis between the steps in which rate was increased and similar tests in which rate was decreased. No oil was produced at any flow rate.

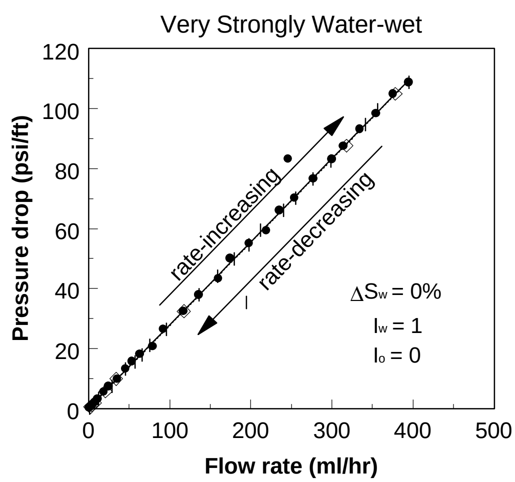

Figure 1. In very strongly water-wet Berea sandstone, the ratio of pressure drop to flow rate of water in the presence of a residual saturation of oil is constant. No oil was produced at any flow rate.

Mixed-wetting

Berea sandstone cores were also used for tests under mixed-wet conditions. Mixed-wetting was produced by exposing cores first to brine, then to one of several crude oils. Typical results are illustrated by tests with Spraberry crude oil and synthetic reservoir brine. Details of the experimental procedures and results with this and other oils are available elsewhere.[2]

Imbibition tests

Cores treated with synthetic reservoir brine and Spraberry crude oil became mixed-wet.[3] Water imbibed more slowly than in a strongly water-wet core (**Fig. 2**).

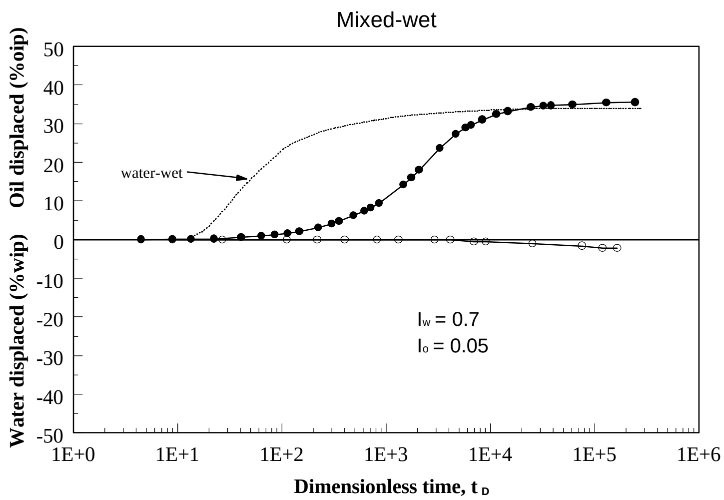

Figure 2. Imbibition rates are indicative of wetting in Berea sandstone cores exposed to synthetic reservoir brine and crude oil from the Spraberry field in West Texas. Dimensionless time is defined by Ma *et al.*, 1997[4] as $t_D = \sqrt{\frac{K}{f}}\frac{s}{\sqrt{m_w m_o}}\frac{t}{L_c}$, **where *K* is permeability, f is porosity, s is interfacial tension, m_w and m_o are viscosities of water and oil, respectively, *t* is time and L_c is a critical length that depends on geometry and the imbibing fluid's access to the core.**

Varying flow-rate tests

In cores rendered mixed-wet, residual oil was established by waterflooding at a low rate. Results are shown in **Fig. 3** for subsequent waterfloods over a range of flow rates. Although the maximum flow rate tested was lower than in the strongly water-wet case, a small amount of residual oil was produced (Fig. 3a). The relationship between pressure drop and flow rate was not constant, especially during the rate increasing portion of the cycle. In subsequent cycles, oil production ceased, but some hysteresis remained between the rate-increasing and rate-decreasing portions of the cycle (Fig. 3b).

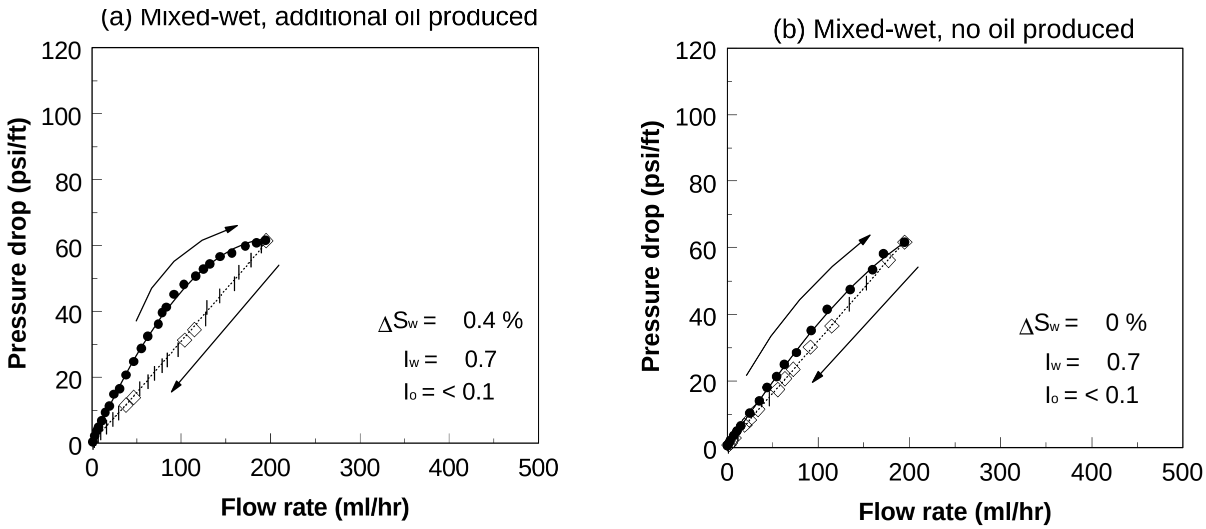

Figure 3. The relationship between pressure drop and flow rate is not constant for flow of water in mixed-wet cores with a residual saturation of oil.

Relative permeability

The flow rate and pressure drop data can be translated into relative permeability end points for the flow of water in the presence of a residual oil saturation, as shown in **Fig. 4**. In the initial high-rate tests, some oil was mobilized and relative permeability to water increases appear to be an extrapolation of the low rate curve. Although there is not universal agreement that this should be so, it is consistent with previous report by Heaviside *et al.*[5] Lower values of critical capillary number appear to apply in conditions that are not strongly water-wet. As the waterflood rate, throughput of water, and time of exposure to high water saturation all increased, the end point relative permeability increased as well, without any corresponding increase in S_w. Waterfloods conducted under these conditions would give not just a different end point, but a completely different relative permeability curve for the flow of water in a mixed-wet core containing oil.

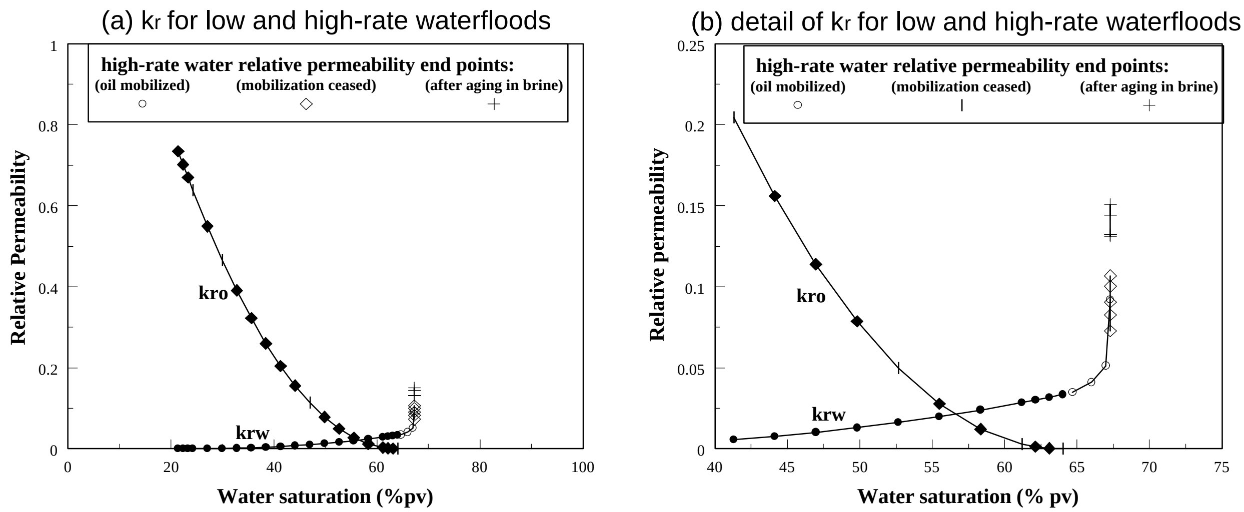

Figure 4. Summary of relative permeabilities from a series of waterfloods at increasing and decreasing rates, including those shown in Fig. 3 above. Initially, small amounts of oil were produced. In these cases, the k_{rw} curve is extended to higher water saturations, but subsequent high-rate test cycles alter the estimate of k_{rw} without change in S_w. Waterfloods conducted after aging the cores in brine for about one month gave even higher estimates of k_{rw}.

Interpretation and Recommendations

In strongly water-wet porous media, oil is trapped in large pores. Permeability to water is maintained through interconnected small pores, as illustrated in **Fig. 5a**. Changes in flow rate below the critical value required to mobilize blobs of oil have little or no effect on the permeability of the rock/oil ensemble to water. The distribution of fluids in a mixed-wet rock is different. The configuration suggested in **Fig. 5b** is just one of many scenarios that could be envisioned depending on contact angles, pore morphology, and remaining oil saturation. Permeability to water might increase if oil is redistributed, with or without appearing at the outlet end of the core. Bridges of oil that may restrict permeability at low flow rates, may break when flow rate increases. While the details of oil redistribution suggested here are purely hypothetical, it does appear to be clear that making some surfaces oil-wet adds a dimension to relative permeabilities that is not evident in studies of strictly water-wet systems. Given the evidence that in mixed-wet systems, relative permeabilities are not unique functions of fluid saturations, the importance of using representative flow rates in laboratory core floods must be recognized. Independent measurements of capillary pressure and local saturation measurements, combined with simulation of waterflood results are needed to provide physically meaningful relative permeability estimates.

(a) strongly water-wet

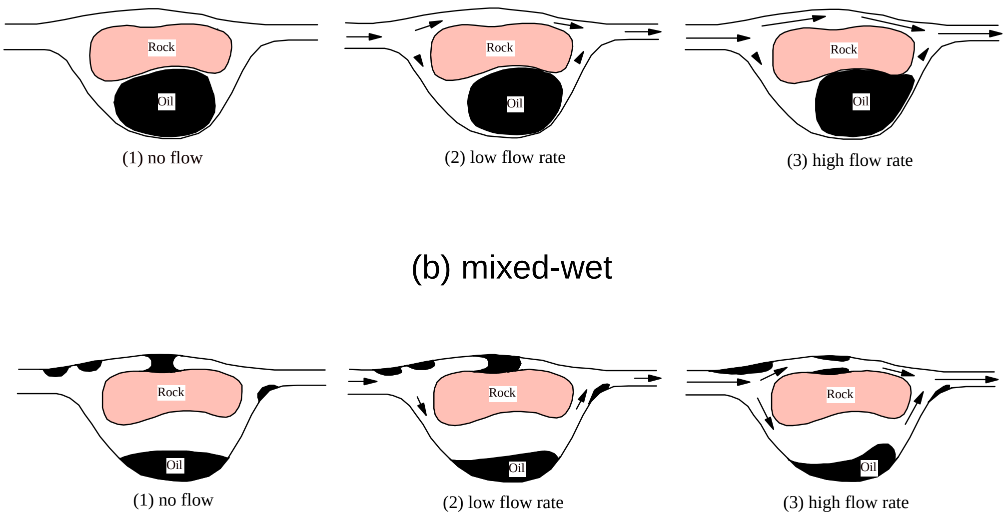

Figure 5. Illustrations of possible mechanisms of entrapment and fluid distribution in a pore doublet. Flow-rate dependence of relative permeability to water in mixed-wet cores may be related to redistribution of oil that occurs in response to increased waterflood rate. Slow redistribution of remaining oil with time at high water saturation may also affect relative permeability without substantially changing fluid saturations.

References

1. Amott, E.: "Observations Relating to the Wettability of Porous Rock," *Trans.*, AIME (1959) **216**, 156-162.

2. Wang, J.X.: "Effects of Wettability on Rate Dependence of Relative Permeability End Points," MS thesis, New Mexico Institute of Mining and Technology, Socorro, NM, April, 1998.

3. Salathiel, R.A.: "Oil Recovery by Surface Film Drainage in Mixed-Wettability Rocks," *JPT* (Oct. 1973) 1216-24; *Trans.*, AIME, **255**.

4. Ma, S., Morrow, N.R., and Zhang, X.: "Generalized Scaling of Spontaneous Imbibition Data for Strongly Water-Wet Systems," *J. Petr. Sci. and Eng.* (1997) **18**, 165-178.

5. Heaviside, J., Brown, C.E., and Gamble, I.J.A.: "Relative Permeability for Intermediate Wettability Reservoirs," paper SPE 16968 presented at the 1987 ATCE, Dallas, Sept. 27-30.