

Gels for Conformance Improvement in Gas EOR Flooding

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Introduction

Gel treatments have been applied to reduce channeling in high-pressure gas floods and to reduce water production from gas wells and enhance oil recovery (EOR). Typically, wells intersect several geologic formations or “zones.” Some of these formations dominantly contain oil; some dominantly contain water; others dominantly contain gas. The objective of applying gel treatments is to substantially reduce flow from some zones (that produce too much water, or sometimes, too much gas) while allowing high production rates for hydrocarbon. When gels are applied for this purpose, we typically inject a solution of polymer and crosslinker, called a “gelant.” This solution will readily penetrate into all available “zones” or formations. At some time after the polymer and crosslinker are mixed (i.e., the gelation time), the two components will react sufficiently to form a gel (e.g., like Jell-o™). This gel is basically fixed in position in the porous rock. When the well is returned to production after placing the gel, the various fluids (oil, water, gas) will have different abilities to flow through the gel to reach the well. In other words, the gel reduces the permeability to oil, water, and gas to different extents. We wish to exploit this property to maximize production of the fluids that we want (hydrocarbon), and minimize production of fluids that we don’t want (water or sometimes gas).

In this report, we investigate how two gels reduce permeability to water and to compressed gases (i.e., carbon dioxide and nitrogen). Studies were performed at 900 psi and 1500 psi using a specially developed core apparatus that allowed a comprehensive sequence of experiments to be performed without depressurizing the core. Since water-alternating-gas (WAG) cycles are often used in high-pressure gas floods, we were especially interested in how well gels withstand exposure to multiple WAG cycles.

Experimental Procedures

Gelants Studied

We investigated two types of gels, including (1) a resorcinol-formaldehyde gel (3% resorcinol, 3% formaldehyde, pH=9.0, 0.5% KCl, 0.42% NaHCO₃), and (2) a Cr(III)-acetate-polyacrylamide gel (1.39% HPAM, 212-ppm Cr(III) (as acetate), pH=5.9, 1% NaCl).

Core Preparation

In all core experiments, we used high-permeability Berea sandstone cores. Typically, each core was 14 cm long with a cross-sectional area of 10 cm². The cores

were cast in a metal alloy. Each core had one internal pressure tap that was located approximately 2 cm from the inlet rock face. The first core segment was treated as a filter, while the second core segment (12-cm length) was used to measure mobilities and residual resistance factors.

Equipment

Two Teledyne Isco Model 500D pumps were used in this work: one for pumping brine and the other for pumping compressed gas. These pumps were ideal for this study because they provided stable flow at the high pressures required. For pressure measurements, we used quartz transducers. A back-pressure regulator was used to maintain high pressures in the cores. Figure 1 shows a schematic of the coreflood setup.

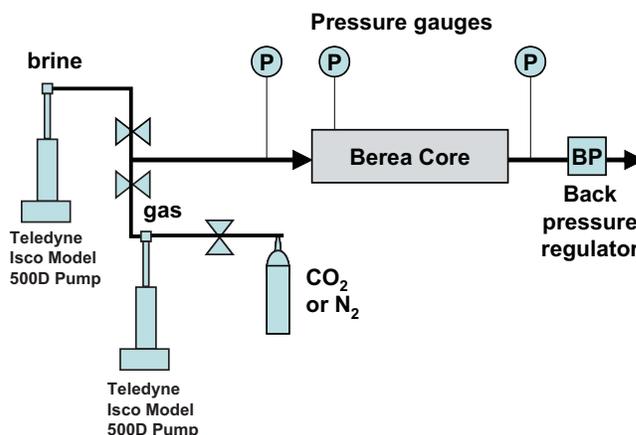


Figure 1: Schematic of the coreflood setup

Flooding Procedures

The sequence followed during our core experiments is listed in Table 1. First, at ambient conditions, the cores were saturated with brine and porosities were determined (Step 1 of the sequence on the following page). All subsequent steps were performed at 41°C. Three experiments were performed at 900 psi (61 atm), while three others were performed at 1500 psi (102 atm). When saturating a given core, the brine composition was the same as that used in preparing the gelant formulation. Cores were mounted so that the flow was horizontal. Steps 1 through 4 were performed to characterize permeabilities, porosities, and brine and gas mobilities. The rock properties were similar for the different core experiments. Brine permeability averaged 650 md, and porosity averaged 0.21. During injection with back pressures of 900 or 1500 psi, the mobility of brine was the same as that at atmospheric pressure.

After the initial saturation of a given core with brine, experiments were conducted entirely at high pressure. Maintenance of a high pressure minimizes complications introduced by gas expansion when cores are depressurized. Following core characterization, we injected 10 PV of gelant, and then shut the core in for three days.

Sequence Followed During Core Experiments with Compressed Gases*

1. Saturate core with brine and determine porosity.
2. Determine absolute brine permeability and mobility.
3. Inject gas to displace brine and determine gas mobility at residual water saturation.
4. Inject brine to displace gas and determine brine mobility at residual gas saturation.
5. Inject gelant using 15.7 ft/d superficial velocity.
6. Shut in core to allow gelation.
7. Inject brine to determine the residual resistance factor for brine (F_{rrw}).
8. Inject gas to determine the residual resistance factor for gas (F_{rrgas}).
9. Inject brine to determine F_{rrw} .
10. Inject gas to determine F_{rrgas} .
11. Inject brine to determine F_{rrw} .
12. Inject gas to determine F_{rrgas} .
13. Inject brine to determine F_{rrw} .

* Except for Step 1, all steps were performed at 41 °C and at high pressure (900 or 1500 psi).

Results

F_{rrw} Values during First Brine Injection – Following the shut-in period after gel placement, brine was injected (Step 7) to determine the residual resistance factor for brine (F_{rrw}). These F_{rrw} values were determined by dividing brine mobility (at residual gas saturation) before gel placement by brine mobility after gel placement. Table 1 summarizes the residual resistance factors from this study. In all cases, these residual resistance factors apply to the second core segment.

F_{rrgas} Values during First Gas Injection – After determining F_{rrw} values, compressed gas was injected to determine the residual resistance factors for gas (F_{rrgas}). These F_{rrgas} values were determined by dividing gas mobility (at residual water saturation) before gel placement by gas mobility after gel placement. Table 1 shows that for all experiments, the residual resistance factors were much lower during gas injection than during the previous water injection.

F_{rr} Values during Re-injection of Water and Gas –

When water was re-injected to displace gas, residual resistance factors were less than the preceding F_{rrw} values. This was noted for both gels (Table 1). Apparently, the gels experienced substantial breakdown during the first WAG cycle. The decrease in F_{rrw} values was most dramatic for those gels with the highest initial residual resistance factors. Additional WAG cycles were performed, and with each new WAG cycle, both F_{rrw} and F_{rrgas} values decreased, indicating further gel breakdown.

One of the most interesting findings of this study was that the F_{rrw} values obtained during Step 9 were significantly greater than the F_{rrgas} values from Step 8. The results indicate that both gels reduce permeability to water more than to gas. Table 1 reveals that this behavior persists through multiple WAG cycles.

Table 1: Summary of Residual Resistance Factors for Brine (F_{rrw}) and Compressed Gas (F_{rrgas})

Flood Step	Core	1	2	3	4	5	6
	Gel	Resorcinol-Formaldehyde			Cr(III)-acetate-HPAM		
	Gas used	CO ₂	N ₂	CO ₂	CO ₂	N ₂	CO ₂
	System pressure, psi	900	900	1500	900	1500	1500
7	F_{rrw} during 1 st WAG	21,600	10,400	19,600	272,000	170,000	4970
8	F_{rrgas} during 1 st WAG	101	126	17	500	284	148
9	F_{rrw} during 2 nd WAG	570	520	23	1720	3440	472
10	F_{rrgas} during 2 nd WAG	60	64	14	50	103	64
11	F_{rrw} during 3 rd WAG	400	484	18	549	1750	177
12	F_{rrgas} during 3 rd WAG	57	61	11	13	81	34
13	F_{rrw} during 4 th WAG	361	370	20	131	1440	94

Performance Using CO₂ versus N₂. After first brine injection with the resorcinol-formaldehyde gel at 900 psi, the F_{rrw} and F_{rrgas} values during the multiple WAG cycles were virtually identical for the CO₂ experiment and the N₂ experiment. The similarity in results suggests that the observed behavior is not sensitive to the type of gas used during this experiment with the resorcinol-formaldehyde gel. To expand on this point, (1) for both compressed CO₂ and compressed N₂, the gel reduced brine permeability significantly more than gas permeability, and (2) multiple WAG cycles degraded the residual resistance factors to about the same extent for CO₂ as for N₂.

A second set of experiments used the Cr(III)-acetate-HPAM gel at 1500 psi. As during the resorcinol-formaldehyde experiments at 900 psi, the gel reduced brine permeability significantly more than gas permeability. The performance of the gels during CO₂/water experiments was not greatly different than that during N₂/water experiments. These results are especially interesting considering the corrosive nature of CO₂ and the inert nature of N₂. One might expect gel formation and stability to be altered by a low pH environment that was created by the presence of CO₂.

Effect of Pressure on Performance. We were concerned that CO₂ behavior at 900 psi (where CO₂ density is 0.156 g/cm³) might be much different than that at 1500 psi (where CO₂ density is 0.641 g/cm³). Therefore, we performed three experiments at 1500 psi—one using the resorcinol-formaldehyde gel and two using the Cr(III)-acetate-HPAM gel. For the resorcinol-formaldehyde gel, a comparison of the results (Table 1) suggests that gel breakdown during the first WAG cycle was more severe at 1500 psi than at 900 psi. However, gel breakdown at 1500 psi was less evident during subsequent WAG cycles. At both pressures, residual resistance factors for water were consistently greater than those for gas.

For the Cr(III)-acetate-HPAM gel, a comparison of the results (Table 1) reveals similarities in behavior at the two pressures. At both pressures, (1) resistance factors were consistently greater for brine than for CO₂ and (2) residual resistance factors decreased during multiple WAG cycles. Although some differences exist in F_{rrw} and F_{rrgas} values during the multiple WAG cycles, the overall behavior at 1500 psi was not radically different from that at 900 psi.

Significance of Results

Our motivation for this study was to assess the use of gels as a means to reduce fluid channeling in CO₂ floods. Since WAG cycles are often used in high-pressure gas floods, we were interested in how well gels withstand exposure to multiple WAG cycles. Our experiments suggest two important deficiencies for gels in this type of application. First, WAG cycles (especially the first WAG cycle) can significantly degrade gel properties. Second, in our experiments, the gels always reduced water permeability much more than they reduced gas permeability. Since gas mobility is usually significantly greater than water mobility, we would like a gel that reduces gas permeability at least as much as it reduces water permeability for applications to control gas channeling in CO₂ injection wells. For both gels studied, the behavior during CO₂/water experiments had many similarities to that during N₂/water experiments. Gel behavior at 1500 psi (where CO₂ density is 0.641 g/cm³) was not radically different from that at 900 psi (where CO₂ density is 0.156 g/cm³).

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