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Hydrodynamic Retention and Rheology of EOR Polymers in Porous Media

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Abstract

Polymer retention caused by increase of hydrodynamic force acting upon polymer molecules was evaluated in this study. The results indicate this hydrodynamic retention is strongly flow rate dependent. In the low-flow region, the retention increases abruptly with increased flow rate. In contrast, in the high-flow region, the increase becomes much more gradual. Our results also demonstrate that this flow-induced retention is totally reversible (no incremental irreversible retention occurs), which is also confirmed by the constant residual resistance factors determined after 100 PV of brine postflush. Consistent with previous literature, distinct flow behaviors of partially hydrolyzed polyacrylamide (HPAM) and xanthan polymers in porous media were observed. For HPAM, in the low-flow regime, Newtonian behavior (i.e., resistance factor is independent of flow rate) was exhibited. In the moderate-to-high-flow regime, HPAM showed shear-thickening behavior (resistance factor increase with flow rate). In contrast, only shear thinning (resistance factor decreases with flow rate) was detected for xanthan polymer. By analyzing the retention and rheology of both HPAM and xanthan polymers, we show that hydrodynamic retention has little effect on polymer rheology in porous media.

Introduction

When water-soluble, high molecular weight polymers are used to reduce water mobility and improve volumetric sweep efficiency, polymer retention delays polymer propagation and oil displacement. Polymer retention comprises adsorption on rock surfaces, mechanical entrapment in small pores, and flow-induced hydrodynamic retention (Gogarty 1967; Szabo and Corp, 1975; Huh *et al*. 1990). In this research, we focus on issues associated with polymer hydrodynamic retention. Previous studies reported that polymer retention increases with increased injection rate (Maerker 1973; Dominguez and Willhite 1976; Aubert and Tirrell 1980; Zaitoun and Kohler 1987; Huh *et al* 1990). However, in the literature, hydrodynamic retention has not been quantified for different flow rates. In this study, we present a method to investigate the variation of hydrodynamic retention with the increase of flow rate. As will be seen, it can also be used to estimate the degree of reversibility of this flow-related retention. Finally, we will address the question of whether rheology of EOR polymers in porous media is retention-dominated (as proposed by Chauveteau *et al*. 1974, 2002) or is more likely an intrinsic property.

Experimental

Polymers: A partially hydrolyzed polyacrylamide (HPAM) (SNF Flopaam 3230S) and a xanthan polymer (CPKelco Kelzan XC, HV) were used in our tests. The polymers were kindly provided by the manufacturers as white granular powders. HPAM is estimated to have a molecular weight of 6-8 million Daltons and degree of hydrolysis of approximately 30%. HPAM solutions were prepared using the magnetic stirrer vortex method. Xanthan solutions were prepared using a blender (four minutes at setting 8 in a 10-speed Hamilton Beach blender). After preparation, polymer solutions were forced through a 10 μm filter to remove any microgels and debris.

Brine: 2% NaCl brine was prepared and filtered through a 0.45-μm filter before application.

Tracer: 40-ppm potassium iodide (KI) was added to the polymer solution as a tracer. Its concentration in the effluent was monitored by a Tunable Absorbance Detector (Waters 486) at a wavelength (λ) of 230 nm as an indicator of brine propagation through porous rock.

Porous Media: A rectangular Dundee sandstone core and a cylindrical Berea sandstone core were used in our tests. The 15-

cm long Dundee core with a permeability of 1.9-darcy was cast in epoxy resin (Core #1 in Table 1). The 13-cm long Berea sandstone core (Core #2 in Table 1) had a permeability of 71-md and was cast in a metal alloy. Two internal pressure taps divided the Dundee core into three sections with lengths of 2.5 cm, 10 cm, and 2.5 cm. The Berea core also had three sections, with lengths of 1.5 cm, 10 cm, and 1.5 cm. Honeywell pressure transducers were connected to the pressure taps to monitor pressure drop during brine and polymer injection.

Table 1-Two sandstone cores used in the tests.

No.	L, cm	A, cm^2	PV, ml	ϕ, %	k, md	Note
1	15	14.5	52.4	24.1	1,900	Dundee
2	13	11.4	27.0	18.2	71	Berea

Experimental Setup. The dynamic method was employed to estimate polymer retention in porous media. This involves two polymer slug injections separated by large pore volumes of brine injection (Lotsch *et al*. 1985; Hughes *et al*. 1990; Osterloh and Law 1998). The purpose of large volumes of brine injection was to flush out all the mobile polymer molecules from the core. The equipment setup and experimental procedures can be found in Zhang and Seright (2014). For most cases, effluent polymer concentration was determined by measuring pressure drop across the 10 μm filter combination connected to the core downstream. However, there were some cases where effluent samples were collected periodically for concentration determination by a total organic carbon (TOC) analyzer. We used a Shimaduz Model TOC—VCSH analyzer for cases where the pressure drop response across the filter was either not sufficiently sensitive (e.g., due to the shear thinning flow rheology of xanthan) or a sudden variation of flow rate disturbed the pressure readings.

Method Established to Detect Hydrodynamic Retention. Polymer retention in a fresh core at certain low flow rate was first determined by the approach described by Zhang and Seright (2014). Specifically, two identical polymer banks were injected at the same flow rate, separated by a substantial brine injection. Retention was determined by the difference in breakout curves when polymer was displacing brine (i.e., subtracting the PV-concentration difference associated with the first polymer bank from that associated with the second polymer bank).

To investigate the impact of flow rate on retention, after the retention was determined at the lower flow rate, two polymer bank injections at a desired high flow rate were conducted which were also separated by large volumes of brine flushing. Two polymer breakout curves at the high flow rate are plotted together with the second polymer breakout curve from the low flow rate as a function of pore volumes injected (see Fig. 1). To simplify the explanation, hereafter, the second breakout curve at low flow rate is called Curve A; the first and second breakout curves at high flow rate are called Curve B, and Curve C, respectively. The total incremental retention is given by the area between the second breakout curve at low flow rate and the first breakout curve at high flow rate, i.e., the area between Curve A and Curve B in Fig. 1. In addition to the total incremental retention, this method can also be used to quantify the incremental irreversible retention and the reversible retention. The principles behind this approach can be summarized as follows:

a) If the area between Curve A and Curve B is zero, it means no incremental retention is induced by flow rate variation. Theoretically, for a purely homogeneous core, if no retention occurs with increased flow rate, these three breakout curves should overlap one another. Fig. 2 demonstrates the retention of 40-ppm KI (used as a tracer) in 1.9-darcy Dundee sandstone core as a function of flow rate. As flow rate increases from 3.26 ft/day through 104 ft/day, all these breakout curves match one another, which implies the retention of this small molecule salt is independent of flow rate.
b) If the area between Curve A and Curve B is not zero, but Curve B and Curve C overlap or the area between these two curves is zero, this implies that there is no incremental irreversible retention. In other words, all the incremental retention due to flow changes can be considered reversible. Additional polymer retained during the first high-rate injection step (Curve B) presumably desorbed during the subsequent brine injection. Then during the next high-rate injection step (Curve C), the same amount of polymer must be retained in order for Curve C to match Curve B. Consequently, we conclude that all incremental retention between Curves A and B must be reversible for this case.
c) If the area between Curve A and Curve B is not zero, but Curve C and Curve A overlap or the area between these two curves is zero, this implies that there is no incremental reversible retention. In other words, all the retention can be considered irreversible. When brine was injected after attaining Curve B, no polymer desorbed. So when polymer was re-injected to generate Curve C, all polymer retention sites were occupied—confirming that polymer was retained irreversibly during the first high-rate polymer injection (Curve B).
d) If the area between Curve A and Curve B is not zero and Curve C falls in between the other two curves (Curves A and B), then the area between Curves A and C gives the incremental reversible retention, and the area between Curves C and B gives the incremental irreversible retention. Of course, the total incremental retention is the summation of these two areas.

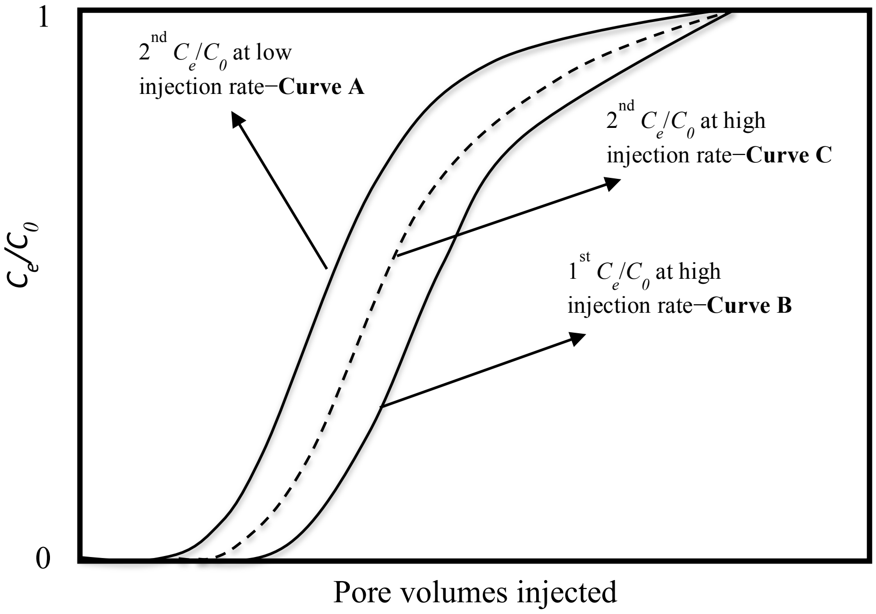

Fig. 1-Schametic of the method to determine hydrodynamic retention.

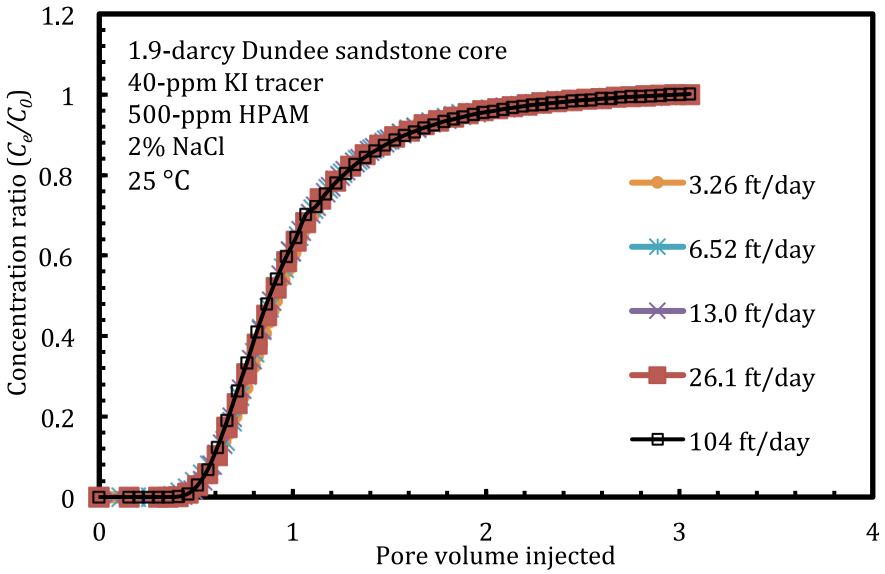

Fig. 2-Dependence of KI (tracer) retention on flow rate.

Notes:

(1) Retention at any other higher flow rate can be estimated by repeating the described procedures. The polymer solution in all these cases should be kept the same.

(2) This method is valid to estimate flow-rate-induced retention based on the assumption that polymer inaccessible pore volume (*IAPV*) is independent of flow rate. If at high injection rate or pressure gradient, polymer solution penetrates into un-swept region which is pre-occupied by brine (not polymer), then polymer *IAPV* will decrease with increased flow rate. If this is true, the phenomenon of *IAPV* decreasing with flow rate increase will also delay polymer propagation and similar scenarios shown in Fig. 1 will be observed. This question will be addressed in a later section.

Results and Discussion

Hydrodynamic Retention in a 1.9-darcy Dundee Sandstone Core

500-ppm HPAM Polymer. The Dundee sandstone core (1.9-darcy permeability and 24.1% porosity) was first used to estimate how flow rate affects polymer retention. As mentioned earlier, retention of 20.4 μg/g rock at a low flux (*u*) of 3.26 ft/day was first measured. Next, the same 500-ppm HPAM polymer solution was injected into this high-permeability core at elevated injection rates ranging from 6.52 ft/day through 104 ft/day. Again, 100 PV of brine were used to flush the core after each polymer slug injection. The results are shown in Table 2 and Fig. 3. Because none of the areas between the second breakout curve at 3.26 ft/day and the first breakout curve at increased flow rate were zero, the total incremental retentions (reversible) as a result of flow rate increase were estimated to be 2.7, 5.7, 8.0, 8.7, and 9.1 μg/g rock as flux increased from 3.26 ft/day to 6.52, 13.0, 26.1, 52.2, and 104 ft/day, respectively.

Table 2-Retention summary.

v, ft/day	Γ_{Total}, μg/g rock	Incremental Γ_{Irrev}, μg/g	Incremental Γ_{Rev}, μg/g rock	RRF
3.26	20.3		0	1.89
6.52	23.0	0	2.7	1.87
13.0	25.7	-0.3	5.7	1.92
26.1	28.3	0.2	8.0	1.86
52.2	28.4	-0.6	8.7	1.89
104	29.5	0.1	9.1	1.90

Notes:

1. Γ_{Total}, Γ_{Irrev}, and Γ_{Rev} = total, irreversible and reversible retention, respectively.
2. RRF=residual resistance factor.

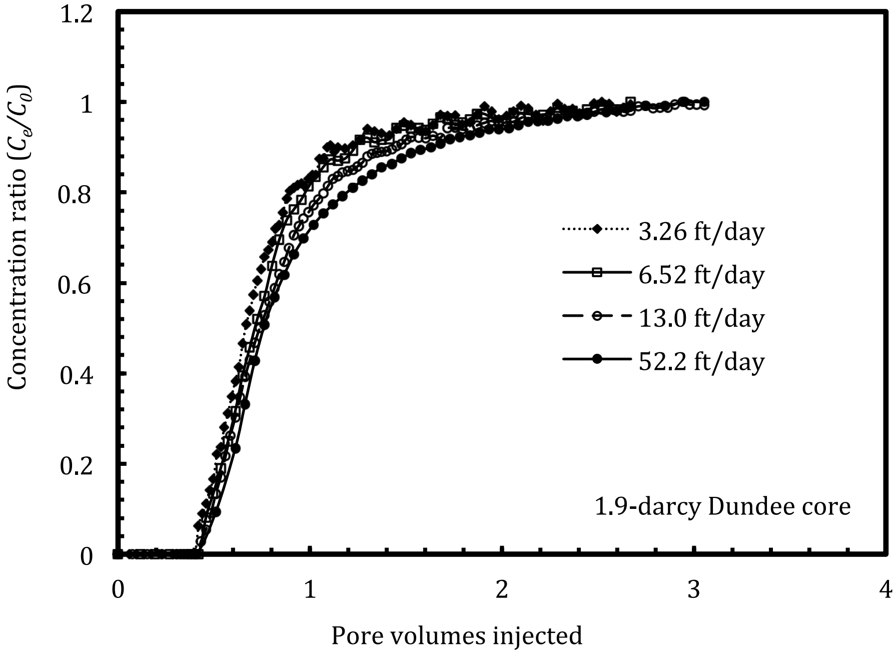

Fig. 3-Breakout curves of 500-ppm HPAM at flow rates from 3.26 ft/day through 52.2 ft/day.

Retention was investigated using flux or superficial velocity values (*u*) from 3.26 to 104 ft/day. These velocities may be encountered during field applications in un-fractured vertical wells. When polymer solution is injected through an un-fractured well (e.g., radial flow), the flow rate varies significantly as polymer penetrates into reservoir. Consider polymer injection into a vertical openhole injector (with a formation height of 20 ft) at a rate of 4,000 bbls/day. Eq. 1 can be used to describe the velocity at which polymer travel through the matrix vs. invading radius, which indicates that flow rate decreases inversely with the increase of distance or the invading radius. For instance, the flux is about 179 ft/day at the radius of 1 ft and it decreases tremendously to 1.79 ft/day at the radius of 100 ft. Though the typical flux deep in a reservoir may be relatively low, the flow pattern in near the wellbore may impact polymer retention. Therefore, it is important to address this issue.

$$u = \frac{179}{r} \quad \text{.......(1)}$$

Where, r is the invading radius of polymer front, ft.

Retention vs. Flow Rate (Flux). We plotted incremental reversible retention (percentage) as a function of velocity in Fig 4. Careful examination of Fig. 4 reveals that different retention trends were observed in different flow regions. For instance, the slope of the low-velocity region (from 6.52 ft/day to 26.1 ft/day) is approximately 19 times greater than that from 26.1 ft/day to 104 ft/day. This implies the incremental retention increases abruptly in the low-velocity region. When the velocity reaches a certain value, the retention rises much more gradually with the increase of flow rate.

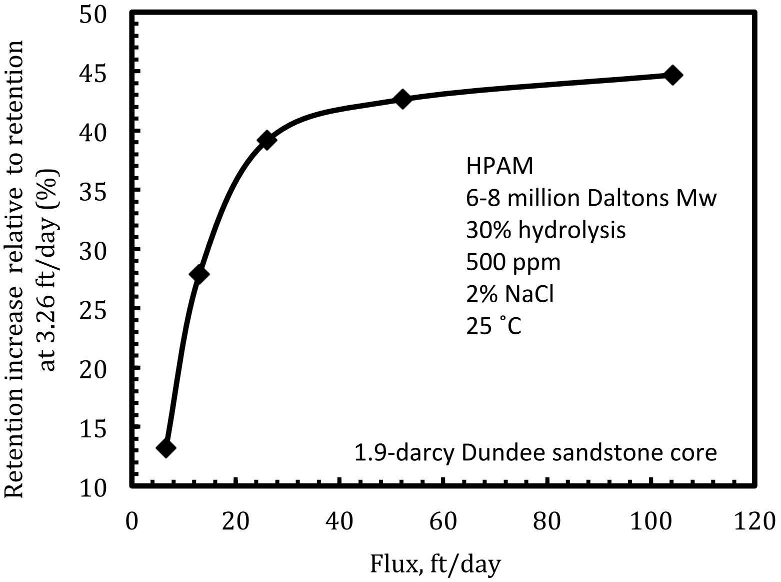

Fig. 4-Incremental retention of HPAM relative to retention at 3.26 ft/day.

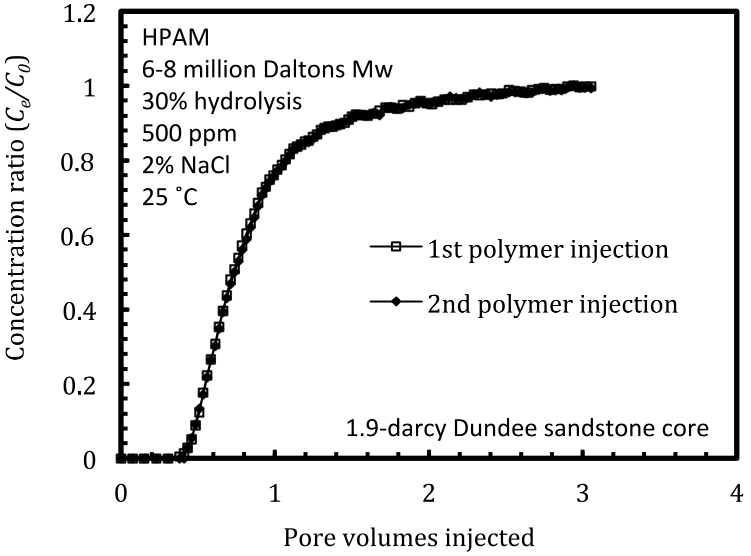

Fig. 5-Determination of irreversible retention at 13.0 ft/day.

Reversibility of Hydrodynamic Retention. For each case, a second polymer bank was injected after 100 PV of brine injection with intervening periods of no flow to check the reversibility of this flow-induced retention. Fig. 5 and Fig. 6 demonstrate the results at flow rates of 13.0 ft/day and 52.2 ft/day, respectively. The area between the first and second breakout curves at same flow rate for both cases is close to zero. Based on the principle explained earlier, it can be inferred that no incremental irreversible retention was detected. In other words, all the incremental retention turns out to be reversible.

These results confirm that 100 PV brine injection in our study is sufficient to displace all mobile polymer from the core. Otherwise, a non-zero area between these two breakout curves should be observed. This also proves that the same core can be repeatedly used for incremental retention measurements at other flow rates, as long as sufficient brine is flushed.

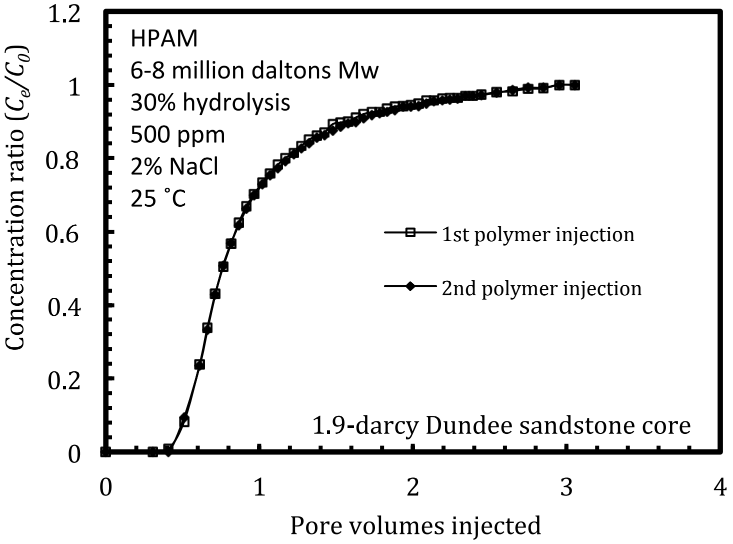

Fig. 6-Determination of irreversible retention at 52.2 ft/day.

Impact of Hydrodynamic Retention on Residual Resistance Factor. How does the hydrodynamic retention affect rock permeability? If all the flow-induced retention is reversible as indicated by Fig. 5 and Fig. 6, there should be no significant permeability reduction caused by this hydrodynamic retention. This postulation was confirmed by residual resistance factor measurements after the core was exposed to 100 PV brine injection for each case. As shown by the last column in Table 2, the residual resistance factors (RRF) was quite stable for all these cases, with values close to 1.9. Little dependence of residual resistance factor on polymer injection rate also verifies that almost all the incremental retention associated with a flow rate increase can be displaced out of the core during postflush with brine. These results generally agree with findings by Maerker (1973) and Dominguez and Willhite (1977). However, our results display a much clearer picture of retention reversibility.

HPAM Polymer Rheology in Porous Media. Polymer resistance factor is defined as water mobility (before exposure to polymer) divided by polymer solution mobility. Resistance factor is a measure of the effective viscosity of a polymer solution in a porous media, relative to water. Pressure drops across the core during both polymer and brine injection were recorded and used to calculate resistance factors at various flow rates. As shown by Fig. 7, except for the highest velocity, this HPAM polymer solution shows either Newtonian or shear thickening behaviors. For instance, at velocity from 3 ft/day to 10 ft/day, HPAM shows Newtonian behavior--i.e., resistance factor is independent of flow rate or shear rate. While, with further increase of velocity from 10 ft/day to 50 ft/day, it becomes shear thickening--i.e., resistance factor increases with flow rate or shear rate. At very high velocity, a decreased resistance factor may be observed. This can be attributed to the viscosity reduction caused by mechanical degradation at high velocity (Maerker 1975; Seright 1983). In field applications, this high velocity is only anticipated near wellbore.

The rheology of HPAM in porous, especially shear thickening, was attributed to the viscoelastic character of HPAM and elongational flow field in porous media (Durst *et al*. 1982; Macosko 1993). In a typical brine solvent, polymer molecules usually take coiled configurations and significant energy is needed to untangle this coil (i.e., to expand and elongate polymer molecules). At low flow rate, polymer molecules have sufficient time to react to the hydrodynamic force acting upon them to become untangled and stretched. Because a stretched polymer molecule always shows less resistance to flow than a coiled one, the resistance factor exhibited in porous media at low flow rate or shear rate parallels the viscosity measured in a viscometer. However, at high velocity, polymer molecules do not have sufficient time to become stretched before they flow through a pore constriction. Hence, more energy (or pressure gradient) is needed to force them through these small pore throats, which results in a high resistance factor at increased velocity. In contrast, the double-helix, rod-like xanthan polymer molecules are already expanded even at low velocities. When they flow through a constricted pore throat, regardless of flow rate, the coil-to-stretched transition is much less significant. Therefore, unlike HPAM polymer, xanthan does not exhibit shear thickening in porous media. The rheology of xanthan polymers will be discussed further in the following section.

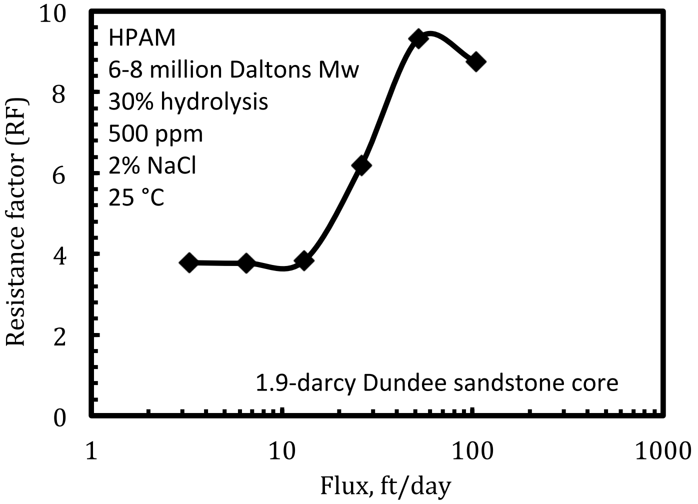

Fig. 7-Resistance factor of HPAM at different flow rates.

Is HPAM Shear Thickening Behavior Caused by Hydrodynamic Retention?

By comparing Figs. 4 and 7, we notice that hydrodynamic retention of HPAM increased with increasing velocity over the same range of velocity values where shear thickening was observed (i.e., 6 to 50 ft/d). Is this shear thickening in porous media a result of retention-related permeability reduction instead of polymer elongational flow mentioned previously? Chauveteau *et al* (1974, 2002) speculated that shear thickening behavior of HPAM in porous could be attributed to hydrodynamic retention which causes permeability reduction. To address this question, another water-soluble EOR polymer, xanthan was tested by following the same procedures. Before the retention measurement, both HPAM and xanthan rheology were measured in an Anton Paar rheometer. Fig. 8 reveals that HPAM and xanthan solutions show similar rheology in the viscometer except for the low concentration HPAM (150 ppm), which behaves more like a Newtonian fluid--i.e., viscosity depends little on shear rate. 150-ppm and 500-ppm xanthan solutions show obvious shear thinning, while 500-ppm HPAM displays a mild shear thinning. Fig. 8 also demonstrates that no shear thickening is seen for HPAM in a viscometer.

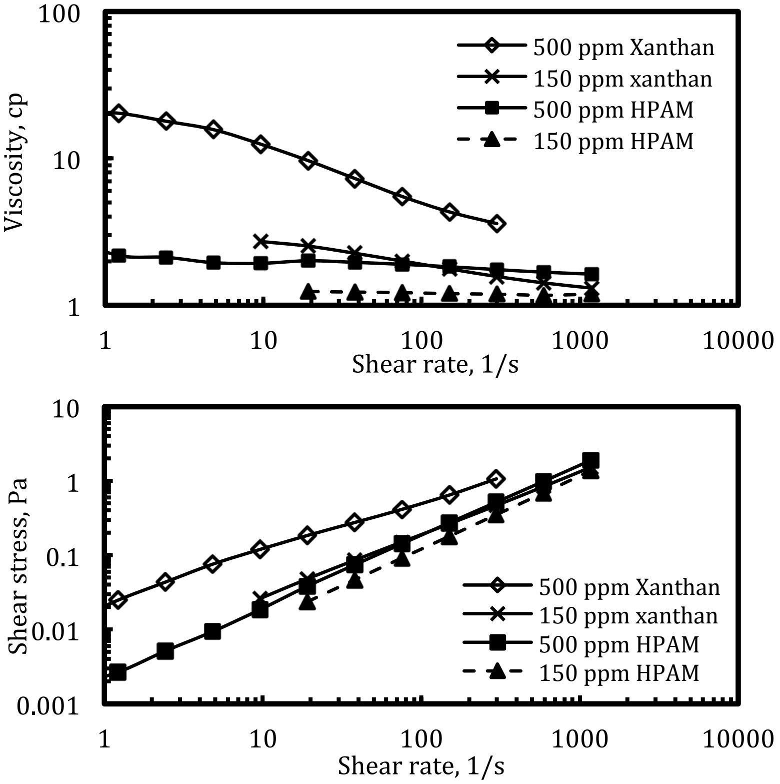

Fig. 8-Rheology of HPAM and xanthan in a viscometer.

Hydrodynamic Retention of Xanthan in 1.9-darcy Core. The same method was used to estimate how xanthan retention varies with flow rate. However, pressure drops across the 10 μm filter combinations during xanthan solution injection were much less sensitive to effluent concentration compared to HPAM solutions. To minimize experimental error, we switched to another approach for effluent concentration determination. Effluent samples were collected periodically for total organic carbon (TOC) content measurement. Fig. 9 plots two normalized concentration ratios (C_e/C_0) as a function of pore volumes injected. One plot is the breakout curve for 3.26 ft/day injection velocity, and the other is for 26.1 ft/day. The area between these two curves gives an incremental retention of only 0.81 μg/g, which is much lower than that from HPAM (8.0 μg/g rock). This difference in retention reveals that different functional groups or molecular size for these two polymers may significantly affect their retention behaviors in the same porous media. Since no appreciable amount of xanthan is retained in this high-permeability core, a less-permeable core was used in a subsequent investigation.

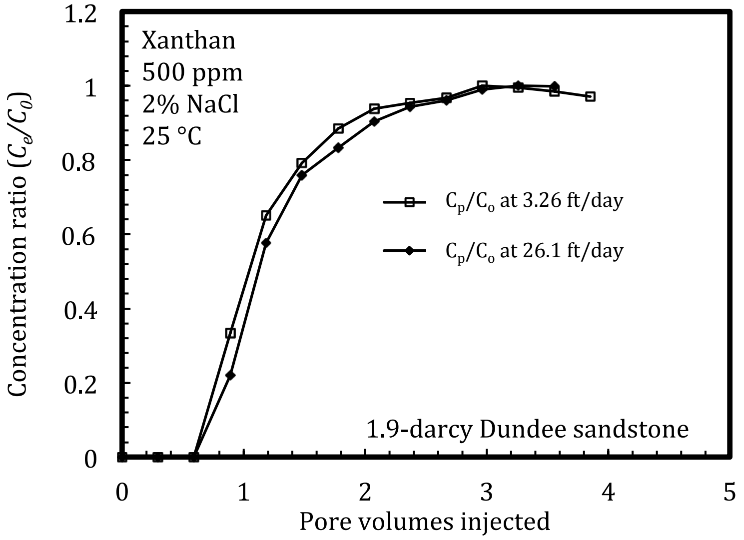

Fig. 9-Hydrodynamic retention of 150-ppm xanthan in 1.9-darcy core.

Rheology of Xanthan in Porous Media. Resistance factors of xanthan polymer in the 1.9-darcy core were measured. As shown by Figs. 8 and 10, xanthan consistently showed shear thinning behavior both in a viscometer and in porous media. Resistance factor was 8.5 at a velocity of 3.26 ft/day. It declined to 5.5 when velocity rose to 52.1 ft/day. These results agree with previous reports (Seright *et al.* 2009, 2010).

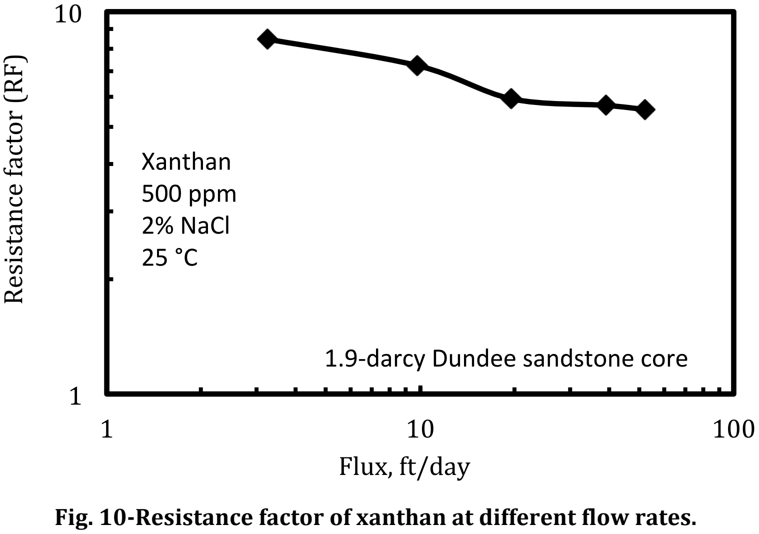

Fig. 10-Resistance factor of xanthan at different flow rates.

Hydrodynamic Retention in 71-md Berea Sandstone Core

As discussed above, a relatively high permeability core may not be a good candidate to capture the retention variation with flow rate for a xanthan polymer. A 71-md Berea sandstone core was selected whose retention had been satisfied with large pore volumes of HPAM polymer injection. Experiments were carefully designed to address two issues: 1) Is rheology of polymer solution in porous media an intrinsic property, or it is dominated by retention related permeability reduction? 2) Does polymer inaccessible pore volume (*IAPV*) decrease with increase of flow rate or pressure gradient? This second question was mentioned previously.

Experiment Procedures. To answer these two questions, the following procedures were designed:

a) Inject 100 PV of brine with intervening periods of no flow to flush out all the mobile polymer molecules in the porous media.
b) Inject polymer solution at a low velocity (u_a) until the effluent concentration is the same as injected. Note: pressure drop across the core was recorded and polymer effluent samples were collected periodically for concentration determination via TOC analyzer.
c) Without any pause, raise velocity abruptly to a level several times higher than the previous one and continually inject polymer solution at this velocity (u_b) until several pore volumes have been injected.
d) Either stop for a while or continue injecting, reduce velocity back to the lower level (u_a) and continue polymer injection until several pore volumes have been injected.
e) Raise flow velocity again from u_a to u_b and complete several PV solution injection.
f) Plot normalized polymer concentration and polymer resistance factor versus PV injected.

Retention and Rheology of 150-ppm HPAM in 71-md Core. Injection of 150-ppm HPAM was first analyzed. We chose a low polymer concentration of 150 ppm so that rheology would be Newtonian for our solution. Fig. 11 shows that when a sudden increase of velocity from 4.14 ft/day to 16.6 ft/day was made after around 4 *PV* injection, an immediate decrease in effluent polymer concentration was detected, i.e., $C_e/C_0<1$. This indicates that additional polymer is stripped from the solution. This phenomenon agrees with the finding mentioned previously for 500-ppm HPAM in a 1.9-darcy core. After around 4 *PV* of injection, the effluent polymer concentration approached the initial polymer concentration. Next, the velocity was abruptly decreased from 16.6 ft/day back to 4.14 ft/day, resulting in a rise of effluent polymer concentration ($C_e/C_0>1$). Again, this demonstrates that the retained molecules were released back into solution when the velocity was lowered. Finally, when velocity was increased once again to 16.6 ft/day, a similar amount of polymer was retained by the porous media. These results confirm our former findings that almost all the hydrodynamic retention was reversible. Comparing these three areas marked as A, B and C in Fig. 11, within experimental error, they are nearly the same—which means almost all the retention was reversible. This test also suggests that polymer inaccessible pore volume (*IAPV*) varies little with increase of flow rate. Otherwise, we would not expect to see these effluent concentration variations with change in flow rate for area B and C.

The rheology of 150-ppm HPAM in this 71-md core was continuously monitored during the whole injection period. As shown by Fig. 11, except at the time when the flow rate adjustment was just made, resistance factor was the same at both injection rates (4.14 ft/day and 16.6 ft/day)—with a value around 12.5. This Newtonian-like rheology was also displayed in a viscometer shown in Fig. 8 (the solid triangle). A similar phenomenon was observed from the previous tests for HPAM in a 1.9-darcy core. When velocity increased from 3.26 ft/day to 6.52 ft/day to 13.0 ft/day, 13% and 28% incremental increases in retention were detected (Fig. 4), respectively, but all the resistance factors stabilized at around 3.8 (Fig. 7). Therefore, rheology of HPAM polymer in porous media appears to be an intrinsic property and should have little dependence on hydrodynamic retention.

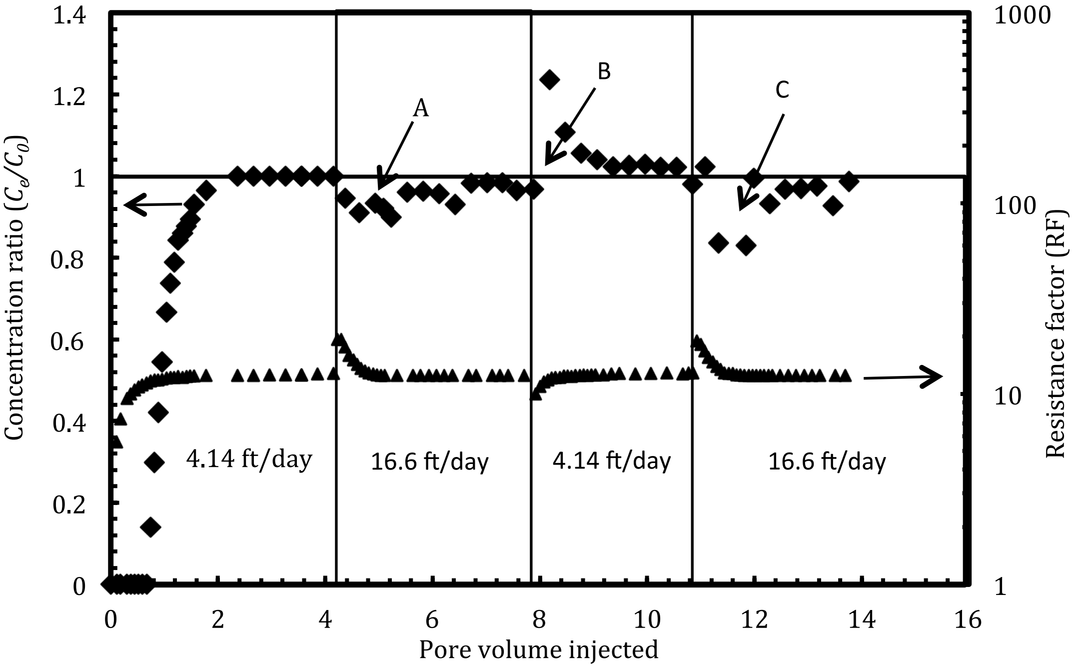

Fig. 11-Hydrodynamic retention and resistance factor for 150-ppm HPAM in 71-md core.

Retention and Rheology of 150-ppm Xanthan in 71-md Core. Similar tests were performed with 150-ppm xanthan polymer. The results are displayed in Fig. 12. Again, as velocity rose from 4.14 ft/day to 33.2 ft/day, more retention in porous media was observed, i.e., the concentration ratio (C_e/C_0) was less than 1. After several pore volumes of polymer injection, the system was shut-in for 2 hours to eliminate hydrodynamic forces from acting on the molecules. When flow was resumed, an effluent concentration higher than the initial concentration was detected (C_e/C_0>1). The highest concentration ratio (C_e/C_0) after the flow resumption was as high as 1.9.

Again, when we checked the polymer rheology in porous media, we found that xanthan exhibits shear thinning behavior. For example, the resistance factor at 4.14 ft/day was 8.04. In contrast, the resistance factor decreased to 5.9 at 33.2 ft/day (see the solid triangles in Fig. 12)—a 30% decrease. This shear shinning behavior in the porous media was consistent with that from a viscometer (Fig. 8).

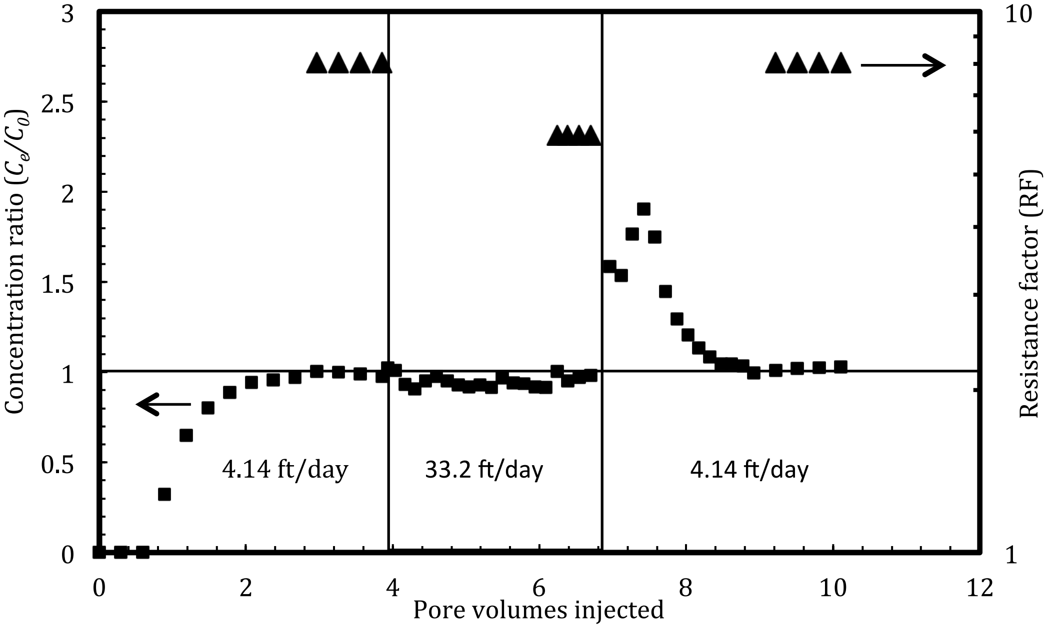

Fig. 12. Hydrodynamic retention and resistance factor for 150-ppm xanthan in 71-md core.

Conclusions

1. Two polymer slug injections separated by 100 PV of brine injection were used to estimate hydrodynamic retention caused by flow rate increase. This method was also able to quantify the incremental reversible retention and irreversible retention associated with flow rate variation.
2. Polymer retention was affected by flow rate, and different extents of flow rate dependence were observed. In the low-flow region, retention increased abruptly with increased flow rate. In contrast, in the high-flow region, the increase of retention became much more gradual.
3. Almost all hydrodynamic retention was reversible. Incremental irreversible retention associated with increased flow rate was negligible. This was also confirmed by constant residual resistance factors for each case, which showed little dependence on flow rate.
4. Consistent with previous literature, distinct flow behaviors of HPAM and xanthan polymers in porous media were observed (i.e., shear thinning for xanthan and Newtonian or shear thickening for HPAM). Analysis showed that rheology EOR polymers exhibited in porous media was an intrinsic property. Hydrodynamic retention had limited effect on flow behavior. Specifically, shear thickening for HPAM was not caused by flow-rate-dependent retention.

Acknowledgement

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Nomenclature

A = core section area, cm^2
C_0 = initial polymer or tracer injection concentration, ppm
C_e = effluent polymer or tracer concentration, ppm
k = permeability, md or darcy
L = core length, cm
r = polymer invading radius in the reservoir, ft
u = superficial velocity or flux of polymer solution, ft/day
u_a = low polymer flux, ft/day
u_b = high polymer flux, ft/day
Γ_{Irrev} = incremental irreversible retention, μg/g rock
Γ_{Rev} = incremental reversible retention, μg/g rock
Γ_{Total} = total incremental retention, μg/g rock
λ = wavelength, nm.
ϕ = porosity

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