Plugging and Improving Oil Recovery Performance of Polyacrylamide Nanogel in Porous Media

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ABSTRACT

The heterogeneity of a reservoir is always a problem during oil production because injection fluids preferentially flow through higher permeability zones. Hydrogel has been used in petroleum industry by plugging high permeability zone to solve the problem in reservoirs. This work investigated the flow behavior of polyacrylamide based nanogel in porous media, which included injectivity, plugging performance and oil recovery improvement. Two factors were controlled in this work: crosslinking density of nanogel and permeability of porous media. Among the nanogels synthesized by four different crosslinker concentrations, swollen particles have a larger size with lower crosslinker concentration. Meanwhile, within a same permeability range, there were higher plugging efficiency and oil recovery improvement with lower crosslinker concentration. Nanogel has a less plugging efficiency but a better oil recovery improvement in lower permeability porous media.

Keywords: enhanced oil recovery, conformance control, gel treatment, nanogel

1 INTRODUCTION

In oil industry, heterogeneity of reservoir can cause two problems during oil production: 1) lower oil recovery. After primary and secondary recovery [1], about 30% of initial oil in place would be produced [2]. 2) excessive water production. Environmentally, produced water damage enivorment as a source of pollution. Economically, excessive water production will cause the corrosion of facilities and the cost of disposing of produced water [3].

Gel treatment has been proved as a cost-efficiency conformance control method. During secondary recovery stage like water flooding, injection fluids always have a trend to go through higher permeability zones, which would cause low sweep efficiency and high remaining oil saturation. Thus, gel treatment is designed to plug higher permeability zones to increase sweep efficiency to obtain higher oil recovery and lower water production. To plug fractures in reservoirs, bigger size preformed particle gels are often applied to improve injection profile. However, bigger size particle gels can not penetrate into low permeability porous media. In this case, smaller size particle gel like micrometer-size or nanometer-size particle gel would be a suitable option. Microgel developed by Institut Français du Pétrole (IFP) and Brightwater® developed by Nalco Company, ChevronTexaco and BP are currently two types of popular smaller size particle gel in oil industry[4, 5]. Previous work showed Microgel has better plug efficiency with lower permeability or higher brine concentration[6]. Meanwhile, both resistance factor and residual resistance factor increased with higher gel concentrations and lower flow rates [7, 8]. Brightwater® could expand from 4 to 10 times under reservoir temperature when it is delivered into the in-depth of a reservoir [9]. Brightwater® is easy to be injected with low injection pressure. After heating, there is a significant post treatment water injection pressure increase [10]. However, the plug efficeincy is limited in high pereambility porous media [11].

Resistance factor (RF) and residual resistance factor (RRF) are two major terms used to evaluate gel treatment. Resistance factor is the ratio between pre-treatment water mobility and gel mobility. Residual resistance factor is ratio between water mobility before and after gel treatment. Mathematically, both factors could be caculate with injection pressures as shown in Equation (1) and (2).

$$F_r = \frac{\lambda_{water}}{\lambda_{gel}} = \frac{k_w}{\mu_w} \Big/ \frac{k_g}{\mu_g} = \frac{\Delta P_g}{\Delta P_w} \quad (1)$$

$$F_{rr} = \frac{\lambda_{water-before}}{\lambda_{water-after}} = \frac{\Delta P_{after}}{\Delta P_{before}} \quad (2)$$

Fr and Frr are residual factor and residual resistance. λ, k, ΔP and μ represent mobility, effective permeability, injection pressure and viscosity, respectively.

2 EXPERIMENT DESCRIPTION

2.1 Materials

Nanogel: Polyacrylamide (PAM) gel was used in this study. As shown in Table 1, there are four types of PAM nanogel samples being used in this work. All four nanogels were synthesized via suspension polymerization. N, N'-methylene bisacrylamide is the crosslinker, which effect the swelling ratio of particle in water.

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Core samples: Berea sandstones with a diameter of 2 inches and a length around 5 inches.

Brine: 1 wt. % NaCl solution.

Oil: Light mineral oil with a viscosity of 33.5 cP.

PAM SAMPLE	Acrylamide /g	Acrylic acid /g	N, N'-methylene bisacrylamide /mg
#A	10	5	37.5
#B	10	5	7.5
#C	10	5	0.75
#D	10	5	0.25

Table 1: Component and proportion of each PAM samples

2.2 Setup

Figure 1 shows schematic diagram of the experiment setup. A syringe pump was used to inject water to accumulator, hence, brine, oil and nanogel would be injected into core samples. The confining pressure was set at 400 psi above injection pressure. There was a pressure sensor connected in front of core holder to collect the injection pressure data. Test tubes were kept at the outlets of the core holder to collect effluents.

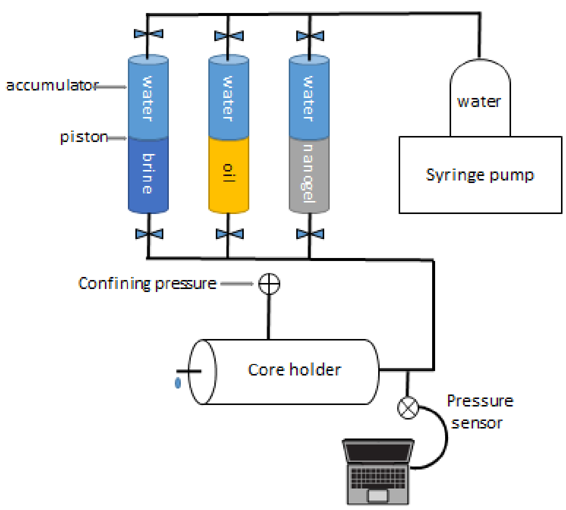

Figure 1: Schematic diagram of experiment setup

2.3 Procedures

All experiments were conducted as the following procedures:

Preparation and saturation of core sample. Core sample were put into oven with 65 ℃ for enough time until there is no water inside porous media. Then the sample was vacuumed for at least 6 hours and saturated with 1 wt. % NaCl brine.

Permeability measurement. 1 wt. % NaCl brine was injected into core samples at multiple injection velocities.

The effluents from next four step were collected to determine the initial oil saturation and oil recovery factors. All injections were stopped only with a stable injection pressure and negligible oil cut (for oil saturation step) or water cut at a pump flow rate at 1ml/min.

Oil saturation. Mineral light oil was injected into core samples to determine initial oil saturation.

First water flooding. Brine would be injected following oil saturation at the same flow rate.

Nanogel treatment. Nanogel particle dispersion was injected into samples at 1 ml/min after fully dispersed in 1 wt. % NaCl brine with a concentration of 2,000 ppm.

Second water flooding. After nanogel injection, another water flooding was performed to determine residual resistance factors.

3 RESULTS

To study the effect of crosslinker concentration, permeabilities of core samples were all around 200mD while different PAM nanogels were tested in each experiment. To study permeability's impact on nanogel treatment, nanogel #A was used in all three experiments with different permeability core samples. Crosslinker concentrations and swollen particle in 1 wt. % NaCl brine are shown in Table 2. Sizes of dry nanogel particle are all round 50 nanometer, which were measured by scanning electron microscope (SEM). Swollen nanogel particle sizes were measured by by Dynamic light scattering (DLS).

Particle	Crosslinker concentration, ppm	Swollen particle size, nm(diameter)
A	1248	354.2
B	250	538.6
C	25	615.1
D	8	955.4

Table 2: Crosslinker concentration and particle sizes

3.1 The Effect of Crosslinker Concentration on nanogel Treatment

During both gel treatment and second water flooding, injection pressure increased slowly at first. After reach a peak, pressure would drop and reach a stable value in the end. The pressure drop is a result of gel strength under high injection pressure. When injection pressure reaches a higher range, nanogel particle is no longer strong enough anymore. Therefore, injection flow would partially break through and result in a pressure drop.

Figure 2 shows the peaks of resistance factors during gel treatment and the resistance factors after a stable gel injection pressure. Figure 3 shows the peaks of residual resistance factors and the stabilized residual resistance factors during second water flooding. The flow rate was 1 ml/min. There is a clear trend that with less crosslinker concentration, which could result in larger particle size, both resistance factors and residual resistance factors are higher. Meanwhile, maximum injection pressures during both gel treatment and second water flooding are also higher with a decrease in crosslinker concentration.

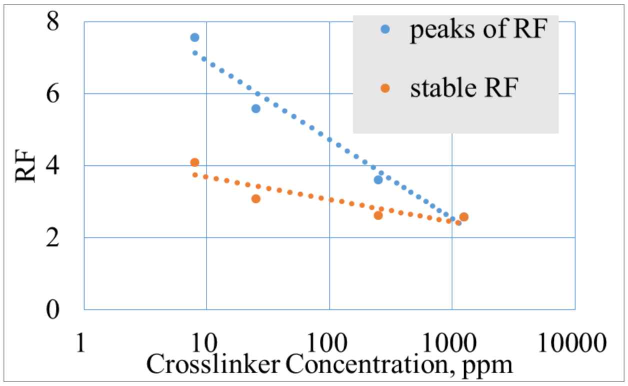

Figure 2: Peaks and stabilized resistance factors

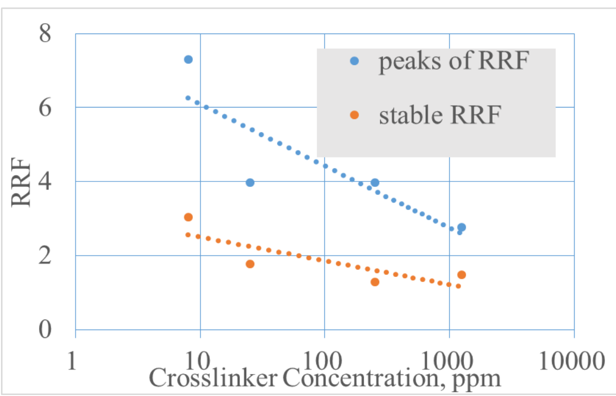

Figure 3: Peaks and stabilized residual resistance factors

Oil recovery factors data are shown in Table 3: when the swollen particles sizes are larger, which means lower crosslinker concentration, there were higher oil recovery increments.

Particle size, nm	Oil recovery factors, %			Oil recovery increment, %
	W.F.	Gel	2nd W.F.	
354.2	45.27	1.73	0.00	**1.73**
538.6	52.88	2.69	0.37	**3.06**
615.1	43.83	4.24	0.00	**4.24**
955.4	53.38	4.44	1.27	**5.70**

Table 3: Oil recovery factors in different stages (W.F.: water flooding; Gel: nanogel treatment; 2nd W.F.: second water flooding)

3.2 The Effect of permeability on nanogel Treatment

Figure 4 shows the peaks of resistance factors during gel treatment and the resistance factors after a stable injection pressure. Figure 5 shows the peaks of residual resistance factors during second water flooding and the residual resistance factors after a stable injection pressure. Both RF and RRF are lower with a decrease of permeability.

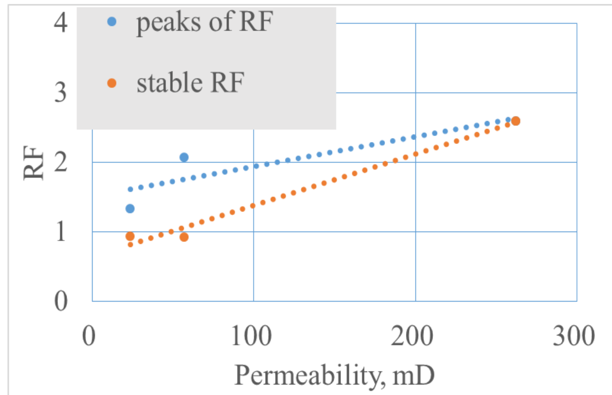

Figure 4: Peaks and stabilized resistance factors

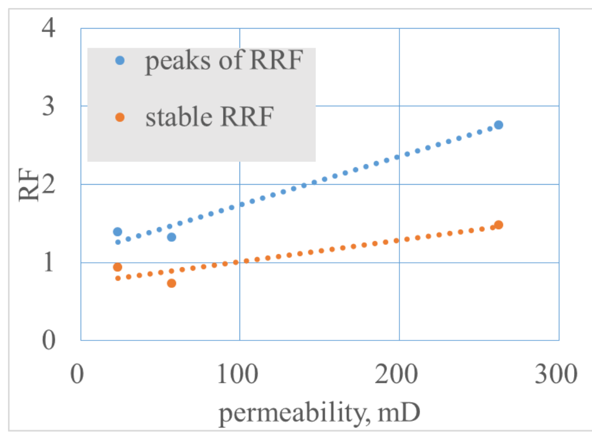

Figure 5: Peaks and stabilized residual resistance factors

Table 4 shows the oil recovery factor data form three experiments. After first water flooding, oil recoveries were all around 45%. When high permeability core sample being used, oil recovery improved by gel treatment is the lowest. When permeability is lower, oil recovery improvement could be higher than 5%. It shows that lower permeability is favorable for improving oil recovery.

Permeability, mD	Oil recover factors, %			Oil recovery increment, %
	W.F.	Gel	2nd W.F.	
262.1	45.27	1.73	0.00	1.73
56.8	47.17	6.13	2.16	8.29
23.4	44.62	4.46	0.92	5.38

Table 4: Oil recovery factors in different stages

3.3 Discussion

The results indicated that within a same permeability range, nanogels with larger swelling ratio have better performance as both oil-displacing agent and plugging agent. In this study, swollen ratio was controlled by crosslinker concentration and all experiments were done with the very same brine. Almohsin el at. [6] controlled swollen particle sizes were by brine concentration. The results showed with higher swollen ratio, nanogel particles were weaker since both resistance factor and residual resistance factor became lower.

When studying the effect of permeability, nanogel had better plugging efficiency in high permeability core sample, but improved oil recovery better in lower permeability core samples.

The high injection pressure is the reason caused the poor plugging efficiency in low permeability core samples. Table 5 shows that the injection pressures of each experiment in the part of study. In lower permeability porous media, injection pressures were much higher. Hence, nanogel particles are no longer strong enough under such high injection pressure.

Permeability, mD	First water flooding stable pressure, psi	Gel injection break through pressure, psi	Stable gel injection pressure, psi	Second water flooding break through pressure, psi
262.1	8.12	21.05	21.05	22.47
56.8	70.30	145.90	65.50	93.00
23.4	232.00	309.80	217.90	322.90

Table 5: Injection pressure at 1ml/min with different permeability

Meanwhile, gel treatment improved oil recovery better with a lower crosslinker concentration or in lower permeability porous media. This result indicates that a higher particle/pore size contrast ratio (larger particles or lower porous media permeability) is favorable for gel treatment to improve oil recovery.

4 CONCLUSIONS

Following conclusions could be drawn from this work.

1. Within a same permeability range, both resistance factors and residual resistance factors increased when crosslinker concentration decreased.

2. For the nanogel synthesized by the same concentration of crosslinker, plugging efficiency become less when permeability was reduced because low permeability rocks required higher injection pressure gradient, which might cause the nanogel particles move out of rocks.

3. Even though all the core samples used in the experiments are homogenous, there are still oil recovery increment during and after gel injection. This indicates that other than conformance control, nanogel could also increase oil recovery by other mechanisms.

4. Oil recovery increment would be higher in lower permeability porous media or with larger swollen nanogel particles. This result indicates that a higher particle/pore size contrast ratio is favorable for improving oil recovery.

REFERENCES

[1] Green, D.W. and G.P. Willhite, Enhanced Oil Recovery. 1997, Richardson, US: Society of Petroleum Engineers.

[2] Terry, R.E., Enhanced oil recovery. Encyclopedia of physical science and technology, 2001. 18: p. 503-518.

[3] Bailey, B., et al., Water control. Oilfield Review, 2000. 12(1): p. 30-51.

[4] Chauveteau, G., et al., New Size-Controlled Microgels for Oil Production. 2001, Society of Petroleum Engineers.

[5] Roussennac, B.D. and C. Toschi, Brightwater trial in Salema Field (Campos Basin, Brazil). 2010, Society of Petroleum Engineers.

[6] Almohsin, A.M., et al., Transport of Nanogel through Porous Media and Its Resistance to Water Flow. 2014, Society of Petroleum Engineers.

[7] Dupuis, G., et al., Successful Chemical Water Shut-Off Treatment in an Omani Field Heavy-Oil Well. 2015, Society of Petroleum Engineers.

[8] Dupuis, G., et al., Water Conformance Treatment using SMG Microgels: A Successful Field Case. 2016, Society of Petroleum Engineers.

[9] Ohms, D., et al., Incremental-Oil Success From Waterflood Sweep Improvement in Alaska. 2010.

[10] Salehi, M., et al., Performance Evaluation of Thermally-Activated Polymers for Conformance Correction Applications. 2012, Society of Petroleum Engineers.

[11] Fabbri, C., et al., Laboratory and Simulation Investigation of the Effect of Thermally Activated Polymer on Permeability Reduction in Highly Permeable Unconsolidated Sand. 2015, Society of Petroleum Engineers.