Flow Properties of EOR Polymers (Part 2) Flow Resistance Properties through Cores

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This paper presents the results of an experimental study on the flow resistance properties of polymer solutions through Berea sand stone cores. The polymers tested in this study were co-polymers of *N*-Vinyl formamide and Acrylamide, respectively.

The ion type and concentration in solution were varied for each polymer in order to examine their effects on the respective flow resistance properties.

Di-valent cations in solution caused greater reduction in flow resistance properties than did the mono-valent cations. Polymers containing AMPS·Na, however, seemed to exhibit higher viscosities and resistance factors in the presence of di-valent cations than those by polymers containing AcA·Na.

The viscosity, resistance factor and residual resistance factor of *N*-Vinyl formamide polymers were not greatly different from those of Acrylamide polymers. The screen factors of *N*-Vinyl formamide polymers, however, were much greater than those of Acrylamide polymers.

1. Introduction

The employment of polymers in water flooding of oil reservoirs had demonstrated some encouraging results in controlling some of the problems associated with conventional water flooding, such as: early breakthrough of injected water and poor sweep efficiency.

These results have triggered increasing popularity of polymer flooding as an enhanced oil recovery (EOR) method, which is evidence of the successful role of polymers as mobility control agents.

Polyacrylamides are the most commonly used synthetic polymers in EOR. Much research results have been published on the flow resistance properties of polyacrylamide polymers in porous media^{1)~3)}. Other synthetic polymers have also been presented in the literature⁴⁾. However, further research may still be required to evaluate their behavior under reservoir conditions.

In this paper, an attempt is made to investigate the flow resistance properties of four polymers of

different chemical structures. Two of these polymers are recently developed co-polymers of *N*-Vinyl formamide and the other two are co-polymers of Acrylamide. The experimental results obtained in Berea sand stone cores are presented.

Polymer solutions were prepared in various concentrations of NaCl and CaCl₂ in water in order to examine the effect of mono-valent and di-valent cations on resistance factor, residual resistance factor, screen factor and viscosity of each polymer.

The flow resistance properties of *N*-Vinyl formamide polymers were compared to those of the Acrylamide polymers to determine which polymer would be better suited for EOR applications.

2. Experimental

2.1 Polymer Samples

The mole ratio of the monomer units and the chemical structures of the four polymers are presented in **Table 1** and **Fig. 1**, respectively. Polymer solutions were prepared in NaCl and

Table 1 Polymer Samples and Mole Ratio of Monomer Units

Sample name	Structure	Mole ratio of monomer units
MS-784	POLY-NVF-co-AMPS·Na	NVF/AMPS·Na=85/15
MS-7917	POLY-AAM-co-AMPS·Na	AAM/AMPS·Na=85/15
MS-7811-27	POLY-NVF-co-AcA·Na	NVF/AcA·Na=85/15
MS-7811-30	POLY-AAM-co-AcA·Na	AAM/AcA·Na=85/15

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Fig. 1 Chemical Structure of Polymers

CaCl₂ brines. The polymer concentration was 1,000 ppm throughout all the experiments and the brine concentration varied from 250 ppm to 100,000 ppm. Excessive shear rates were avoided during mixing and handling of polymer solutions to prevent any loss in viscosity due to degradation. Before injection into the core, the polymer solutions were filtered through a 200 mesh stainless steel screen to prevent micro-gels from entering the core.

2.2 Core Samples

Berea sand stone was used as the porous medium. Core samples of approximately 2.5 cm diameter and 7.5 cm length were prepared for the flow tests. The core samples were heat-treated at 800°C for 10 h to stabilize the clay material. The core sample was then placed inside a flexible tubing supplied by Pennito Co., Ltd. This tubing shrinks upon application of heat to its surface, which seals the core tightly.

2.3 Core Flooding Apparatus

The core flooding apparatus is shown schematically in Fig. 2. The main components of the system are the constant rate pump, the core sample, the pressure measuring unit and the chart recorder.

Kerosene is pumped into a displacement vessel containing the brine or polymer solution to be injected into the core. The core inlet is connected to two pressure transducers having different pressure measuring ranges, and the transducers are in turn connected to an amplifier and a chart recorder. Pump pulsations are minimized by installing a damper at the pump outlet. The vacuum system and the brine reservoir *R* shown in Fig. 2 are used to evacuate the core before filling it with brine to determine its pore volume and porosity.

Fig. 2 A Schematic Diagram of the Core Flooding System

AM	: Amplifier	Pi	: Measuring pipette
D	: Damper	R	: Brine reservoir
DV	: Displacement vessel	REC	: Chart recorder
G	: Pressure gauge	T	: Liquid trap
Ma	: Manometer	Tr	: Transducer
Mu	: Multimeter	VP	: Vacuum pump
P	: Constant Pressure pump	V	: Valve

The core is initially flooded with brine. The flow rate and pressure drop are measured when steady state conditions are reached, and the permeability is then determined. Following flooding with brine, the polymer solution is then injected into the core, and the flow rate and pressure drop are recorded. Finally, brine is again injected. All flooding tests were conducted at a velocity of approximately 10 ft/day and a constant temperature of 25°C.

2.4 Viscosity and Screen Factor

The viscosity is determined by a rotational viscometer capable of providing accurate measurements within a shear rate range of 20–400 sec⁻¹. Apparent viscosity values were determined at a shear rate of 38.3 sec⁻¹. The screen factor measurements were carried out using a screen viscometer containing a pack of five 0.63 cm, 100 mesh stainless steel screens. The time required to flow through the screens in seconds is measured for a constant volume of polymer solution and water.

The screen factor is determined as the ratio of time required for water flow to that of polymer solution. A more detailed description of the screen viscometer is given in Reference 5.

3. Experimental Results and Discussion

3.1 Flow Resistance Properties

Mobility is defined as the ratio of permeability to viscosity. Reduced mobility attributed to polymer solution is called the resistance factor and is determined experimentally from the measure-

ments of the pressure drop across the core sample and the flow rate at the effluent end for flow of water and polymer solution. The equation governing the linear flow of incompressible fluids through porous media is the Darcy equation:

$$Q = k/\mu \cdot A \cdot \Delta P/L \quad (1)$$

By applying the Darcy equation to both flow of water and polymer solution through the same core sample, the resistance factor is determined as:

$$RF = \frac{(k/\mu)_w}{(k/\mu)_p} = \frac{(\Delta P/Q)_p}{(\Delta P/Q)_w} \quad (2)$$

where $(k/\mu)_w$ and $(k/\mu)_p$ are the water and polymer solution mobilities, respectively.

The residual resistance factor is determined from the ratio of the mobility of water before and after injection of polymer.

$$RRF = \frac{(\Delta P/Q)_{\text{after}}}{(\Delta P/Q)_{\text{before}}} \quad (3)$$

3.2 NaCl Brine

Figure 3 shows a plot of viscosity, resistance factor, residual resistance factor, and screen factor *vs.* NaCl concentration in water. The residual resistance factor remained nearly unchanged throughout this range of NaCl concentration. Viscosity, resistance factor, and screen factor decreased with increasing NaCl concentration. This decrease is due to the effect of NaCl in reducing the size of polymer in solution by neutralizing the electrical charge on the polymer. As the NaCl concentration is increased, the polymer chains tend to recoil and take on a spherical shape. This reduces the polymer-solvent contact and, as a result, the viscosity is reduced. At very high NaCl concentrations, the electrical

charge of polymer is completely neutralized by the excess free counter ions in solution, and the polymer behaves as if it is non-ionic⁶.

In Fig. 3 is shown that a small increase in NaCl concentration causes a greater reduction in viscosity compared to screen and resistance factors. This is mainly attributed to the different shear rates at which these properties are measured. In Part I of this study, the effect of NaCl concentration on viscosity was determined at different shear rates. The extent of viscosity reduction by increased NaCl concentration was observed to depend on the shear rate.

The residual resistance factor did not change with NaCl concentration. This may suggest that two opposing effects occur as the NaCl concentration increases: one is the increase in polymer adsorption on the rock surface and the other is the reduction in the size of adsorbed polymer.

3.3 CaCl₂ Brine

Plots of measured flow properties *vs.* CaCl₂ concentration for polymer MS-784 are shown in Fig. 4. The effects of mono-valent and di-valent cations in brine on the resistance properties can be seen by comparing Figs. 3 and 4. No significant difference between the effects of mono-valent and di-valent cations on the resistance factor was observed from these data.

The reduction in the viscosity and screen factor attributed to di-valent cations is much greater than the reduction caused by mono-valent cations. This can be seen in Figs. 5 and 6 for polymer MS-784.

3.4 Polymer Structure

Plots of viscosity *vs.* NaCl and CaCl₂ concentrations, respectively, are shown in Figs. 7 and 8. The AMPS-Na co-polymers seem to tolerate di-valent cations better than the AcA-Na co-polymers.

A comparison between the effects of mono-valent and di-valent cations in brine on the

Fig. 3 Flow Resistance Properties *vs.* NaCl Concentration for Polymer MS-784

Fig. 4 Flow Resistance Properties *vs.* CaCl₂ Concentration for Polymer MS-784

Fig. 5 Effect of Brine Concentration on the Viscosity of MS-784

Fig. 8 Influence of CaCl_2 Concentration on Viscosity for Four Polymers of Different Structures

Fig. 6 Effect of Brine Concentration on the Screen Factor of MS-784

Fig. 9 Effect of NaCl Concentration on Resistance Factor for Four Polymers of Different Structures

Fig. 7 Influence of NaCl Concentration on Viscosity for Four Polymers of Different Structures

Fig. 10 Effect of CaCl_2 Concentration on Resistance Factor for Four Polymers of Different Structures

resistance factor for the four polymers can be made by examining **Figs. 9 and 10**. The AMPS-Na copolymers showed higher resistance factors in the presence of di-valent cations than the Aca-Na copolymers.

Plots of screen factor *vs.* NaCl and CaCl_2 concentrations, respectively, are shown in **Figs. 11 and 12**. For the four polymers, the reduction in screen factor attributed to di-valent cations was

much greater than that caused by mono-valent cations. It is also observed from the two figures that screen factors of the *N*-Vinyl formamide copolymers are much lower than those of the Acrylamide copolymers.

Screen factors are a measure of the extentional flow properties of polymer solutions^{7),8)}. High screen factors can be a disadvantage because they indicate that a given polymer solution may exhibit

Fig. 11 Effect of NaCl Concentration on Screen Factor for Four Polymers of Different Structures

Fig. 12 Effect of CaCl_2 Concentration on Screen Factor for Four Polymers of Different Structures

high resistance to flow in situations where extensional flow takes place. In oil reservoirs, fluid flow rates at distance away from the injection well are very low. Higher flow rates (shear rates), however, may occur near the well bore. These high shear rates may initiate visco-elastic behavior of some polymer solutions and, consequently, injectivity problems may be encountered.

Although this study revealed some differences in the resistance properties of the polymers tested, it is still not possible to predict which polymer is better suited for EOR applications in high salinity environments. Further tests at higher temperatures are also required for better evaluation of polymer resistance properties under typical reservoir conditions.

4. Conclusions

From the discussion of the results obtained in

this experimental study, the following conclusions are presented:

- (1) Viscosity, resistance factor, and screen factor decreased with increasing salt concentration in brine. The residual resistance factor, however, remained nearly constant.
- (2) Di-valent cations caused larger reductions in viscosity and screen factor compared to mono-valent cations. No appreciable difference, however, was observed in the effects of mono-valent and di-valent cations on the resistance factor.
- (3) In the presence of di-valent cations, the AMPS-Na polymers showed relatively higher viscosities and resistance factors than the AcA-Na polymers.
- (4) Screen factors of *N*-Vinyl formamide polymers were much lower than those of the Acrylamide polymers.

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Nomenclatures

- A = Cross sectional area of core
- K = Permeability
- L = Length of core
- ΔP = Pressure drop
- p = Polymer
- Q = Flow rate
- μ_a = Apparent viscosity
- w = Water

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要 旨

EOR 用ポリマーの流動特性について (第 2 報)

コア内の流動抵抗

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この研究は, 第 1 報に引き続き, 2 種類の同様な化学構造を持つ *N*-Vinyl formamide と Acrylamide のそれぞれについて, Berea 砂岩の流動抵抗, すなわち Resistance factor, Residual resistance factor を計り, さらに Screen factor, 回転粘度計による粘度の測定を行い, ポリマー濃度や塩水中の 1 価, 2 価イオン濃度の影響を 25°C で調べたものである。

これらの結果から 2 価イオン Ca^{++} を含む塩水の場合は, 1 価イオン Na^{+} の場合より著しく抵抗係数が減少する。しかし, AMPS・Na を含むポリマーは AcA・Na を含むポリマー

より粘度および抵抗係数が 2 価イオンを含む場合にいくらか高くなるが, 1 価イオンの場合は余り変化が見られなかった。*N*-Vinyl formamide ポリマーは Acrylamide ポリマーに比べて, 粘度, 抵抗係数, 残留抵抗係数ともに余り大きな変化は見られなかった。しかし, Screen factor に関しては *N*-Vinyl formamide ポリマーのほうが, Acrylamide ポリマーより非常に低くなった。これらの結果は, ポリマーの選択に当たって考慮すべき重要な要素であると言える。

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Keywords

Polymer flood, *N*-Vinyl formamide, Acrylamide, Resistance factor, Screen factor, Viscosity