

DETERMINATION OF RHEOLOGICAL PROPERTIES OF POLYMER SOLUTIONS IN SANDPACKS

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(First Received April 1992; accepted in revised form November 1992)

ABSTRACT

There is a correlation between mobility ratio and oil recovery by water displacement in homogeneous and heterogeneous reservoirs. Because of this correlation, it is essential to develop a mobility control process which would be based on the behavior of the mobility ratio factor. It appears that polymer solution is an ideal additive to control the mobility ratio in the operation of waterfloods.

This paper describes the rheological behavior of polymer solutions in sand packs and frontal advance rates. Empirical correlations have been developed experimentally to estimate polymer mobility and displacement efficiency in porous medium. The correlations are based on petrophysical properties of the medium, polymer concentration and polymer rheological parameters.

NOMENCLATURE

C	Polymer concentration
K	Consistency Index C^n
K_{rw}	Relative water permeability
K_{ro}	Relative oil permeability
n	Flow behavior index, dimensionless
λ_o	Oil mobility, md/cP
μ	Viscosity, cP
μ_w	Water viscosity, cP
μ_o	Oil viscosity, cP
λ_w	Water mobility, md/cP
λ_p	Polymer solution mobility, md/cP
γ	Shear rate, Second^{-1}
S_{or}	Residual oil saturation, %
S_{iw}	Irreducible water saturation, %
S_{wb}	Water saturation at breakthrough %
q	Flowrate, ml/sec
q_w	Water flow rate, ml/sec
q_o	Oil flow rate, ml/sec
f	Fractional flow

INTRODUCTION

With the growing understanding of waterflooding aspects, more attention has to be drawn to the development of improved waterflooding techniques. Unfortunately, simply getting the injected fluid to contact a given volume of the reservoir does not mean that all the oil in that volume will be displaced.

The displacement efficiency is a function of fluid viscosities and relative permeability characteristics of reservoir rock (mobility ratio), of the rock wettability and of pore geometry. An obvious approach to improving the mobility ratio would be to increase the effective viscosity of the injected water before injection into the reservoir (Craig, 1971 and Willhite, 1986).

The oil recovery performance of waterfloods can be improved by methods that increase the oil displacement efficiency, the volumetric sweep efficiency or both. These improved methods involve the addition of solvent, heat and chemicals (surfactant, polymer). Polymer flooding is chemically augmented waterflood in which small concentrations of chemicals such as polysaccharide or acrylamides are added to injected water to increase the effectiveness of the water in displacing oil. The design of a polymer flood programme requires knowledge about the polymer flow characteristics and rheological behavior of polymer solutions in porous media. In the absence of experimental data, mathematical models based on a bundle of capillaries could be used to predict polymer mobility in porous media. But results obtained from these models do not often agree with the experimental data (Duda *et al*, 1983 and Shabib *et al*, 1991). An empirical method to predict the apparent viscosity of polymer solutions in porous media has been developed by Gogarty (1967). In this method, a model for the shear rate in a capillary was adopted to the porous medium through correlating parameters obtained from the experimental data. This correlation technique provided a good agreement between the predicted and observed apparent viscosity of polycrylamides solution in sandstone core samples.

This paper describes the flow and rheological characteristics of polymer solutions in sandpacks over a definite range of permeabilities. The objective of this study is to develop correlations for the mobility of polymer solutions in sandpacks as a function of porous medium properties and rheological properties of polymer solutions.

POLYMER SOLUTIONS AS MOBILITY CONTROL AGENT

Polymer applications in oil recovery are centered on thickening of injection water with water soluble polymers and either use as diverting agents or in the consequent improvement in mobility ratio and an increase of sweep efficiency. The

polymer solutions are in general non-Newtonian in behavior (Archer, 1986).

When a waterflood is assumed to be piston-like, oil flows at interstitial water saturation ahead of the sharp front while water flows at residual oil saturation behind the front. The mobility ratio for a very sharp front displacement is given by the equation (Willhite, 1986).

$$M = \lambda_D / \lambda_d \quad (1)$$

Where λ_D is the mobility of the displacing phase behind the front and λ_d is the mobility of the displaced phase ahead of the front.

For waterflood under piston-like displacement

$$\lambda_D = \lambda_w = (K_{rw} / \mu_w) S_{or} \quad (2)$$

and

$$\lambda_d = \lambda_o = (K_{ro} / \mu_o) S_{iw} \quad (3)$$

The mobility ratio (M) is now given by the equation

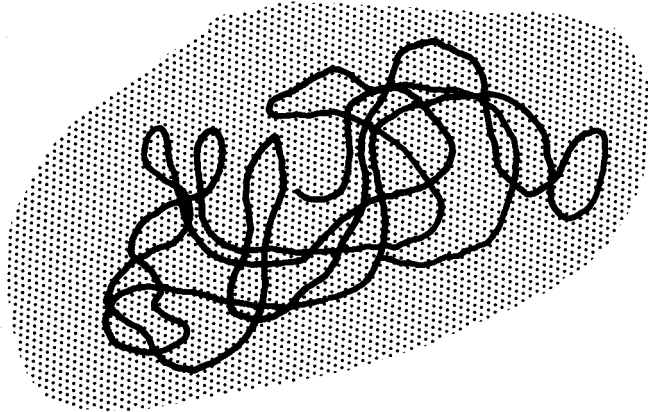
$$M = (K_{rw} / \mu_w) S_{or} / (K_{ro} / \mu_o) S_{iw} \quad (4)$$

If oil mobility is larger than water mobility ($M < 1$) which is usually not the case, the oil moves faster than the water. However, if the oil mobility is less than the water mobility ($M > 1$), the water moves faster than the oil leading to fingering and low oil recovery. Thus the mobility is considered unfavorable when it has a value greater than 1.0 and favorable when the mobility ratio is less than 1.0. Correlations have been developed which relate the mobility ratio to aerial sweep efficiency for different flood patterns. It is found that highly efficient displacement is achieved for M less than 1.0 and gradual decrease in aerial sweep efficiency would be developed for mobility ratios greater than 1.0 (Craig, 1970 and Jennings *et al*, 1971).

Inspection of parameters which can be managed to improve the mobility ratio of a water displacement process leads to the inevitable conclusion that either the permeability of water or the viscosity of water or both have to be handled to modify the mobility ratio. The easiest approach towards developing a mobility control process is to increase the water viscosity. Developments in the field of polymer chemistry provided many new molecules to be considered as potential mobility control agents. Certain polymers exhibited increasing flow properties when dissolved in water. One of these properties is the large increase in solution viscosity which occurs when a small quantity of polymer is dissolved in water (Ferrer, 1972).

In order to understand the role of polymer as mobility control agent by increasing the viscosity of displacing fluid, the structure of the polymer as mobility control agent by increasing the viscosity of displacing fluid, the structure of the polymer molecule in aqueous solution needs to be examined. Figure 1 shows a

polymer molecule dissolved in water. It is seen that, it is long chain twisting around in a random way. This long chain may be broken if violently agitated. The viscosity increasing feature of polymers lies in its large molecular weight which is accentuated by the anionic repulsion between polymer molecules and also between segments on the same molecule. The molecular weight of a polymer range from 1 to 10 million. The interaction between these large polymer molecules with free solvent would increase the viscosity of the solution (Willhite, 1975).



Molecular Weight 1-10 million

Fig. 1: A representation of a polymer molecule in aqueous solution, (Willhite, 1975).

Polymer solutions have appeared as an ideal mobility control agent. However, the polymers suffer from retention in rock matrix due to adsorption. This polymer retention varies with polymer concentration, salt content, permeability and presence of certain cations e.g. Ca^{+} , Mg^{++} . Typically the retention is of the order of 10 to 200 micrograms of polymer per gram of rock. During displacement of oil by polymer solution in a porous medium containing residual water saturation, a water bank is created between the oil and the polymer solution. This water bank contains both connate water and injected water whose polymer content has been lost to the rock matrix. The main effect of polymer retention is to increase the amount required to obtain the desired mobility control, (Sandiford, 1964, Camilleri *et al*, 1987, and Koning *et al*, 1988).

The rheological behavior of polymer solutions is complex. The polymer solutions are non-Newtonian and behave in a pseudo-plastic manner (shear thinning) in the free state, their viscosity decreasing with increasing stress. However, when diluted

in porous media, their viscosity increases as the speed of circulation increases (Latil, *et al*, 1980).

Two types of polymers have been developed as mobility control agents. The first polymer is polysaccharide which is formed from the polymerization of saccharide molecules. Polysaccharide or biopolymer is produced by bacterial fermentation and a suitable carbohydrate. The fermentation process produces cells of 0.3 - 0.5 microns in diameter and 0.7 to 2.5 microns in length, (Lipton, 1974). The second polymer is a partially hydrolyzed polyacrylamide (Fig. 2). Both polymers have unique properties and these problems need to be recognised in the design of a mobility control process, (Bradley, 1987). In this study, polyacrylamide (Nelco's Q 41 F) was used. This polymer is supplied in liquid concentrate with 30% by weight active material.

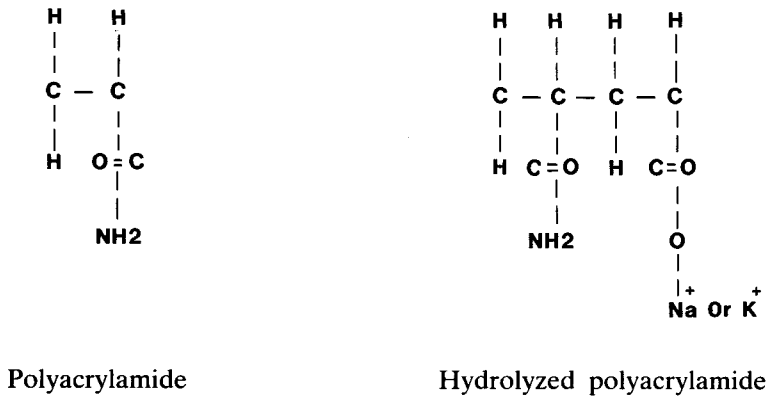


Fig. 2: Molecular structure for partially hydrolyzed polyacrylamide, (Bradley, 1987).

EXPERIMENTAL WORK

Materials

The polymer supplied was polyacrylamide in liquid phase. The concentration of active material is 30% W, determined from the viscosity-based calibration curve. Polymer solutions were prepared at concentrations of 500, 1000, 1300 and 1500 ppm. Before polymer flooding, master batch of 1000 ppm was prepared and filtered through a filter cake. It is found that the polymer solution viscosity has not been affected significantly by filtration. Thus, polymer concentration does not change due to filtration. Polymers of different concentrations were prepared based on the master polymer. The viscosity of polymer solutions with different concentrations was measured by Haake (VT 500) viscometer.

Experimental Apparatus

A schematic section of the experimental arrangement for water/polymer flooding is shown in Fig. 3. Sandpacks 17 cm long and 1.5 cm internal diameter were prepared from south of Oman sandstone reservoir rocks in the coreholder. Pressure drops were measured between the inlet and outlet of the sandpack. The sand in the coreholder was confined by sealing plugs at the inlet and outlet and by pressure ports to prevent leakage. Sandpacks were placed in controlled room temperature conditions. The apparatus is equipped with two containers (one for oil and second for driving fluid). Sandpacks were prepared from the sandstone rocks of definite range of permeability and porosity. The polymer solutions or water displacement system consisted of two pumps, one for displaced fluid and other for displacing fluid.

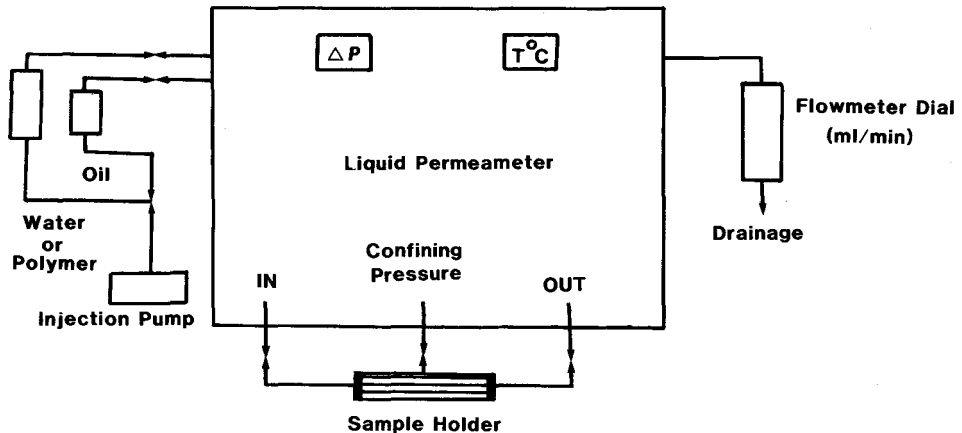


Fig. 3: Schematic of experimental arrangement.

RESULTS AND DISCUSSIONS

Because of the complexity of the subject, a comprehensive treatment of polymer rheological properties is not possible. However, a qualitative trend, few quantitative relations and representative data are presented on properties like, Viscosity relations, non-Newtonian effect and polymer degradation. Simulated polymer/water flooding were prepared in the laboratory.

Viscosity Relations and Non-Newtonian Effect

A non-Newtonian fluid is a fluid that does not show linear relationship between shear stress (τ) and shear strain rate ($\dot{\gamma}$), i.e fluid viscosity (μ) is not constant. A fluid whose viscosity decreases with increasing shear rate is shear thinning. The

polymer is pseudoplastic and at all concentrations follow the power-law model given by:

$$\mu = K (\dot{\gamma})^{n-1} \tag{5}$$

Rheological data for the injected polymer solutions were obtained with Haake Viscometer. Viscosities were obtained in a sequence of steady state shear measurement, over a shear range of 80 to 650 second⁻¹. Figure 4 illustrates the rheograms for four polymer concentrations of 500, 1000, 1300 and 1500 ppm. It is seen, that the polymer viscosity is decreasing with increasing shear rate for all concentrations. Table 1 shows the power law model parameters K and n, determined from the regression of the viscosity shear rate data.

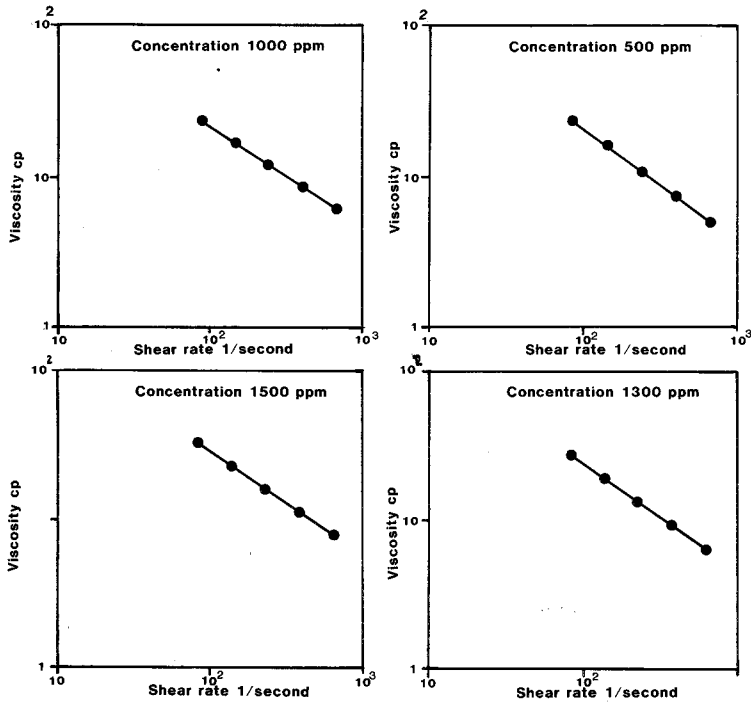


Fig. 4: Effect of shear rate on polymer solution viscosity for different concentrations.

Table 1
Power Law Model Parameters

Concentration "C" ppm	500	1000	1300	1500
Consistency Index "K"	60	66	70	84
Flow-behavior Index "n"	0.31	0.24	0.21	0.15

The relationship between K and n parameters and polymer solution concentration has been identified. The correlations between power law model parameter K and n and polymer concentration C are expressed by

$$n = 1/(1 + 0.0013 C^{1.128}) \tag{6}$$

and

$$K = -51.947 + 17.669 \text{ Ln } C \tag{7}$$

The shear thinning behavior of the polymer solutions is believed due to the uncoiling and unsnagging of the polymer chains when they are placed in a shear flow conditions.

Correlations between polymer solution concentrations and viscosity have been developed. Figure 5 shows the relationship between polymer solution viscosity and concentration. Table 2 summarizes the data shown in Figure 5. It is possible to understand why the polymer viscosity increases with concentration by examining the structure of a polymer molecule in aqueous solution (Fig. 1). It is visualized as a relatively long chain of molecules which twist around in a random orientation.

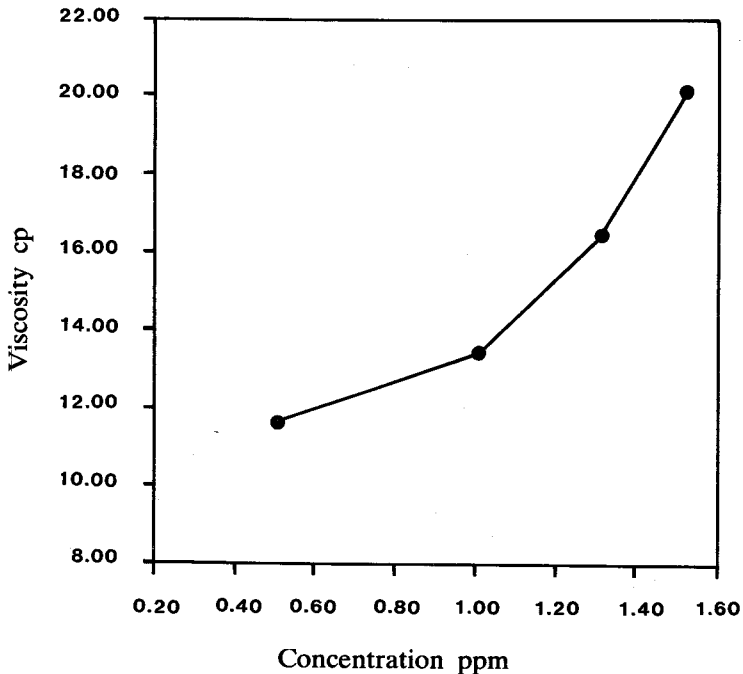


Fig. 5: Change of polymer viscosity with concentration.

Table 2
Polymer Viscosity - Concentration

Polymer Concentration ppm	500	1000	1300	1500
Polymer Viscosity cp	11.7	13.5	16.5	20.1

Polymer Degradation

The most serious limitation for polyacrylamide solution is its sensitivity to degradation. Chemical and biological degradation cause a decrease in polymer molecular weight. Chemical degradation can be minimized by restricting polymer usage to low temperature applications and by adding oxygen scavengers to polymer solution. Biological degradation can be eliminated by adding oxygen scavengers and bio-acids. Mechanical degradation on the other hand is potentially present under all applications. Mechanical degradation occurs when polymer solutions are exposed to high velocity flows. These can be present in surface equipment and in downhole conditions, (Maerker, 1976 and Shupe, 1981).

Figure 4 shows the rate of viscosity loss for different polymer concentrations as a function of shear rate. These losses in viscosity suggest that the design of the mobility control process should be based on solution viscosity when high shear conditions are anticipated.

Polymer Flooding

For two-phase flooding, common specializations of equation 4 are the end point mobility ratio and the average mobility ratio. For incompressible linear horizontal system with no capillary pressure effect, the fractional flow (f) of displacing fluid is related to mobility ratio (M).

In oil-water system, the fractional flow (f_w) is defined as

$$f_w = \frac{q_w}{q_w + q_o} = \frac{M}{1 + M} \quad (8)$$

In oil-polymer solution system, the fractional flow (f_p) is defined as follows:

$$f_p = \frac{q_p}{q_o + q_p} = \frac{M}{1 + M} \quad (9)$$

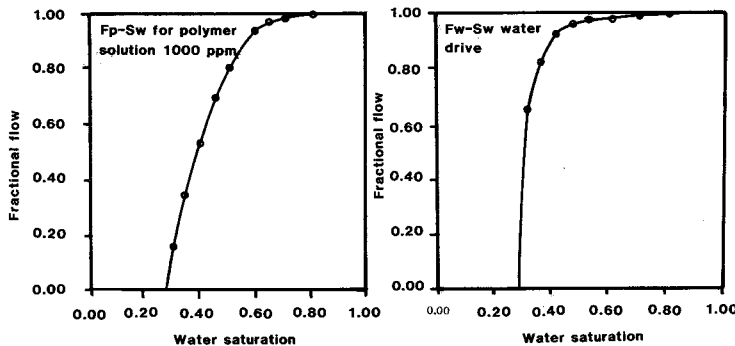


Fig. 6: Fractional flow plots for polymer and water drives.

To develop simulated flooding (water/polymer), the experimental arrangement as shown in Figure 6 was used. An unconsolidated sandpack is used with metering pump for water/polymer solution injection and a pressure gauge measuring monitor. The confining pressure is kept constant at 2000 psi and pressure drop varied depending on the condition of each sample. A graduated fluid collector is connected to the outlet of the sandpack to measure the volume of displaced fluid at the outlet. The flow rate of displacing fluid is measured at the inlet by observing the volume of fluid pumping out of the tank and spent time. The volume of displaced fluid is measured by identifying the volume collected in the graduated collector at the outlet and corresponding time.

The water wet core sample was fully saturated with oil, then it was subjected to water injection from the water tank. The core sample was cleaned, dried and saturated again with oil, then was flooded by polymer solution flow from the polymer solution tank. The fractional flow curves are calculated for water flooding using equation 8 and for polymer using equation 9 respectively. The analysis of fractional flow curves, (Fig. 6) demonstrates the improvement of sweep efficiency of water flooding due to water thickening by viscosity increase. The relative permeability is assumed to be same for both polymer solution and water. The water viscosity varied from 1. cP to 13.5 cP (1000 ppm polymer solution). The average water saturation S_{wb} behind the front up to the time of breakthrough for polymer is greater than that (S_{wb}) for waterflooding. This saturation difference reflects the degree of improvement of the reservoir recovery by using polymer solution.

CONCLUSIONS

1. Polymer solution viscosity increases with the polymer concentration within the range of 500-1500 ppm.
2. Empirical relationships were developed between power-law model parameters and polymer concentrations.
3. The polymer viscosity decreased due to mechanical degradation. This property demonstrates the necessity of considering the anticipated shear conditions in the well bore during the application of polymer flooding.
4. Water thickening (increasing water viscosity) by adding polymer improved the efficiency of water flooding operation.

ACKNOWLEDGEMENTS

I would like to thank Petroleum Development Oman (PDO) for the supply of core samples. My thanks go to Professor Sushil Bhandari for his critical review of

the manuscript and the technicians of Petroleum and Mining Engineering Department, Sultan Qaboos University, for their help and assistance.

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