SHORT COMMUNICATION - PRODUCTION ENGINEERING

Viscosity of partially hydrolyzed polyacrylamide under shearing and heat

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Abstract Polymer flooding is the most successful chemical method to enhance oil recovery. This technique has achieved large-scale field application in China. Polymer flooding is also being tested in several heavy oil fields. For oil field applications, partially hydrolyzed polyacrylamide (HPAM) is the most widely used polymer. HPAM must maintain high viscosity to achieve good oil recovery. In reality, however, polymers can be severely degraded by shearing and heat in the underground environment. This phenomenon is studied in this paper. The two HPAM test samples have molecular weight of 10 million and 20 million. The samples were added to water to achieve concentrations of 500 to 3,000 ppm. The first group of tests was conducted to study the effect of shearing on HPAM viscosity. The second group of tests was carried out to evaluate the effect of high temperature up to 90 °C on HPAM viscosity. It was discovered that both shearing and high temperature can severely reduce polymer viscosity. Data analysis shows that the empirical power law parameters are strong functions of polymer concentration and temperature. Simple formulas are proposed to correlate HPAM viscosity with shearing rate, polymer concentration and temperature. These formulas are useful tools for predicting HPAM viscosity in field applications.

Keywords HPAM · Viscosity · Shearing strain · Degradation · Power law

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Introduction

During oil production, water is often injected into reservoirs to sweep oil into the production well. Because oil viscosity can be much higher than water viscosity, injected water moves faster than oil, leaving oil behind. This phenomenon is referred to as viscous fingering. Polymer can be added to the injected water to retard viscous fingering. Polymer increases the viscosity of injected water, reduces water mobility, and therefore achieves a more stable displacement (Littmann 1988).

Polymer flooding has become the most successful chemical method for enhanced oil recovery (EOR). For the Daqing oil field in China, polymer flooding has contributed to more than 10 % of enhanced oil recovery (Wang et al. 2009). This technology is also being tested in heavy oil fields (Gao 2011). For field applications, partially hydrolyzed polyacrylamide (HPAM) is the most widely used polymer, due to its relatively cheap price and good solubility in water. The molecular structure of HPAM is given in Fig. 1 (Sheng 2010).

Polymer solution is a non-Newtonian fluid that follows the power law given in Eq. 1, where μ is the viscosity (C_p), γ is the shear rate (1/s), k is the consistency index, and n is the flow behavior index (Rabia 1985). If the power law parameters (k and n) can be determined, then the polymer solution viscosity is easily calculated under any shear rate.

$$\mu = k\gamma^n \tag{1}$$

Polymer solution must maintain high viscosity to mobilize oil in reservoir. However, polymer often suffers from viscosity loss due to shearing, heat and salinity that exist in wellbore and reservoir (Gao 2011). HPAM degradation has been studied for many years. In the 1970s, it was concluded that shearing largely depresses
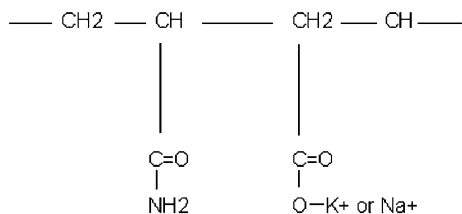
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Fig. 1 Structure of HPAM

HPAM viscosity (Mungan 1972; Maerker 1975). But in a recent article, some researchers argue that shearing has a very slight effect on flow of HPAM in real reservoir (Seright et al. 2011). A study on temperature effect demonstrated that HPAM is stable up to 90 °C in fresh water (Ryles 1988). In China, a polymer flooding project with HPAM proved successful in a reservoir whose temperature was at 75 °C (Chen et al. 1998). Salinity also greatly impacts HPAM viscosity (Needham and Doe 1987; Ward and Martin 1981), but the salinity effect is not covered in this paper.

Unfortunately, it is still a challenge to correctly predict the viscosity of HPAM under shearing and thermal degradation. This paper studies these phenomena through laboratory testing and builds correlations for viscosity of HPAM solution. This work can improve the understanding of flow of polymer solution in underground environment.

Materials and methods

Two HPAM samples, coded as 3,100 and 3,200, were supplied by a polymer producer in the form of powders. The molecular weight of product 3,100 was around 10 million, and that of product 3,200 was 20 million. For both products, the degree of hydrolysis was around 25 %. Polymer powder was added to distilled water and stirred for 48 h to ensure good mixing.

The first group of tests was conducted to study the effect of shear rates on polymer viscosity. The tested polymer concentrations ranged from 500 to 3,000 ppm. The shear rates ranged from 1 to 1,000 s^{-1}. All tests were conducted at the relatively low temperature of 30 C. The second group of tests was conducted to study the effect of high temperature on polymer viscosity. The test temperature was controlled at 50, 70 and 90 °C. The shear rate was controlled at 1, 10, 100 and 1,000 s^{-1}. The tested polymer concentration was 1,500 ppm.

All viscosity measurements were conducted by a torque-type viscometer. During tests, strain was forced by a motor and the generated torque was detected by transducer. The device could measure shear rates ranging from 0.1 to 1000 s^{-1}. The temperature was controlled by a circulator.
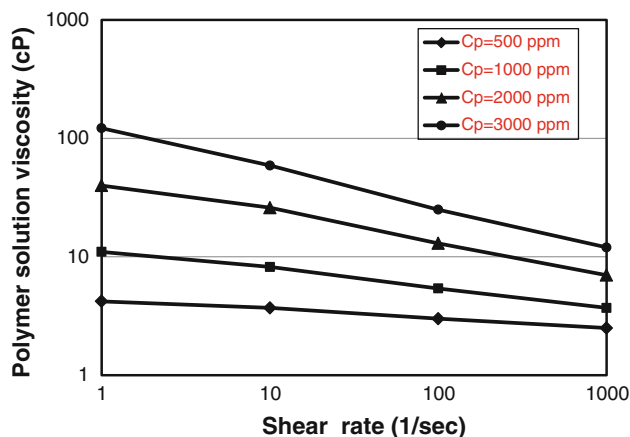

Fig. 2 Viscosity data at different polymer concentrations

Experimental results

The viscosity data for the product 3,100 at 30 °C are given in Fig. 2. The trend clearly complies with the power law. Similar test results were obtained for the product 3,200. It is obvious that higher HPAM concentration leads to higher viscosity. It can also be concluded that polymer viscosity is reduced at higher shear rate.

The test results for the product 3,100 at elevated temperatures are given in Fig. 3. The trends are close to power law relationship. Similar test results were obtained for the product 3,200. It can be seen that polymer viscosity decreases at higher temperature.

Discussions

In this section, effort is spent on studying the numerical relations between the power law parameters, polymer concentration and temperature. Based on the test data, the power law parameters (k and n) can be obtained via curve fitting. For the first group of tests, the temperature was
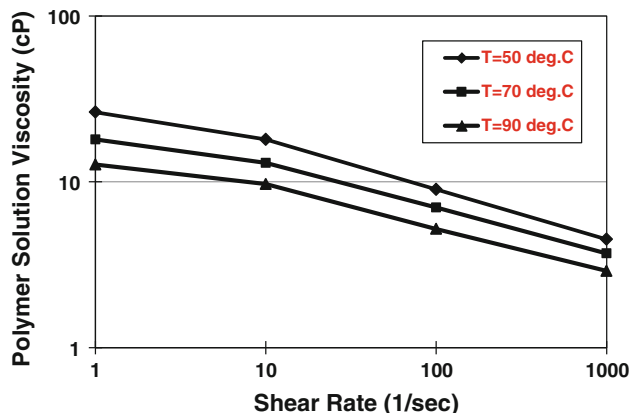

Fig. 3 Effect of temperature on polymer viscosity

Table 1 Power law parameters for the first group of tests

Polymer product	Polymer concentration (ppm)	Temperature (°C)	k	n
3,100	500	30	4.28	−0.077
	1,000		11.33	−0.160
	2,000		42.64	−0.257
	3,000		123.81	−0.339
3,200	500	30	6.45	−0.123
	1,000		24.35	−0.244
	2,000		103.20	−0.390
	3,000		275.94	−0.480

Table 2 Power law parameters for the second group of tests

Polymer product	Polymer concentration (ppm)	Temperature (°C)	k	n
3,100	1,500	50	28.90	−0.260
		70	19.00	−0.233
		90	14.00	−0.220
3,200	1,500	50	73.70	−0.373
		70	57.42	−0.360
		90	39.43	−0.331

Fig. 4 Relationship between polymer concentration and parameter k

Fig. 5 Relationship between polymer concentration and parameter n

fixed while the polymer concentration was varied, as seen in Table 1. For the second group of tests, the temperature was raised while the polymer concentration was constant, as seen in Table 2. It can be seen that the consistency index k increases with increasing polymer concentration, but decreases with increasing temperature. On the other hand, the flow behavior index n decreases with increasing polymer concentration, and only slightly increases at higher temperature. It can also be observed that polymer concentration affects parameters k and n more than the temperature.

Figure 4 plots the relationship between the parameter k and the polymer concentration (Cp). Figure 5 plots the relationship between the parameter n and the polymer concentration (Cp). It is clear that the two HPAM products follow similar trends. Because the two products have the same degree of hydrolysis and similar molecular structure, the small difference is possibly due to the difference in molecular weight. The generalized relationships can be expressed as Eqs. 2–4, where a, b, c, and d are empirical parameters. Equations 3 and 4 can be used to predict HPAM viscosity at 30 °C, if the polymer concentration is known.
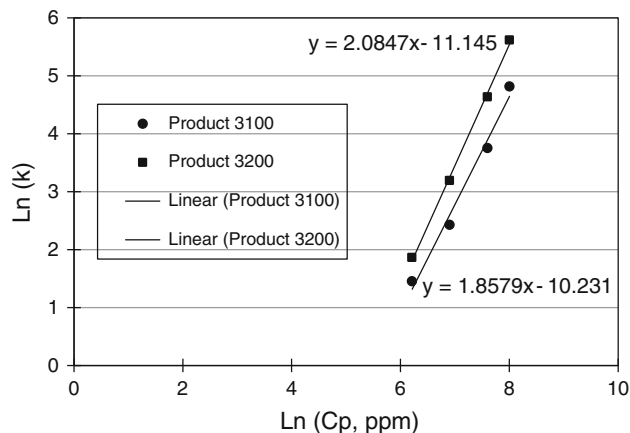
$$\ln(k) = a \ln(Cp) + b \tag{2}$$
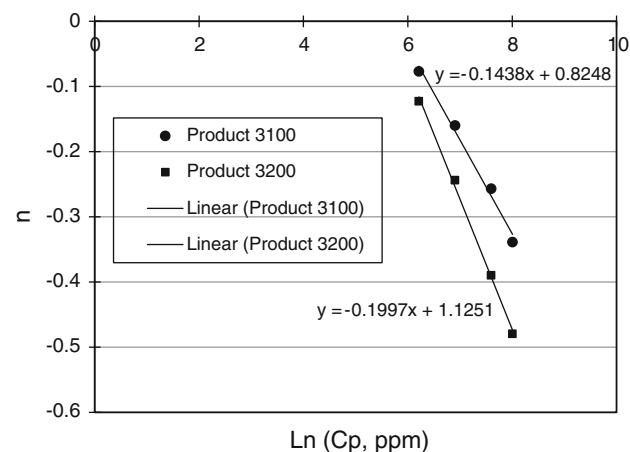
or

$$k = Cp^a e^b \tag{3}$$

$$n = c \ln(Cp) + d \tag{4}$$

Figure 6 plots the relationship between the parameter k and the test temperature (T). Figure 7 plots the relationship between the parameter n and the test temperature (T). It is clear that the two HPAM products follow similar trend. The small difference is possibly due to their different molecular weights. The generalized relationships can be expressed as Eqs. 5–7, where e, f, g and h are empirical parameters. Equations 6 and 7 can be used to calculate HPAM viscosity at high temperature.

$$\log(k) = eT + f \tag{5}$$

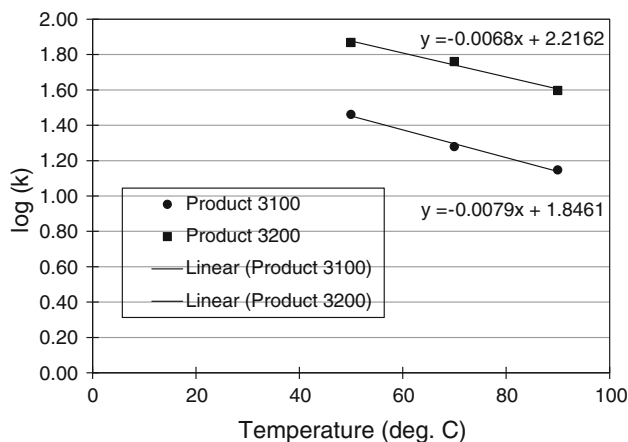or

$$k = T^e \times 10^f \tag{6}$$

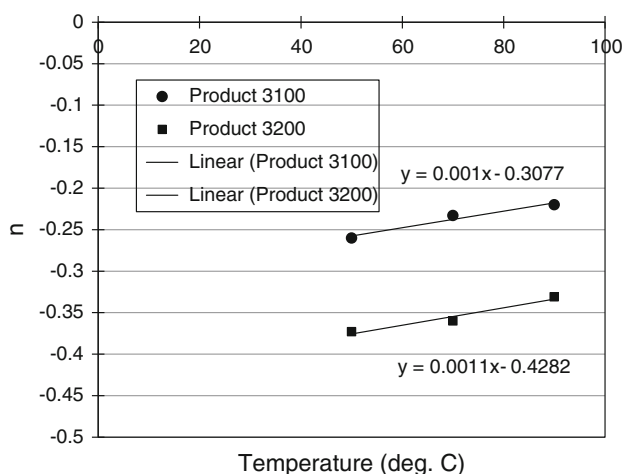**Fig. 6** Relationship between temperature and parameter k

Fig. 7 Relationship between temperature and parameter n

$$n = gT + h \tag{7}$$

The proposed equations are valid for HPAM products. The limitation is that they cannot be used for other polymers. However, HPAM is the only commercial polymer used in polymer flood operations. These equations are therefore considered useful for practical purposes.

Conclusion

The effects of shearing and thermal degradation on HPAM viscosity are studied in this paper. Experimental results demonstrated that both shearing and heat have negative impacts on HPAM solution viscosity. Simple correlations are established to determine the HPAM solution viscosity at a wide range of shearing rates and temperatures up to 90 °C. In the future, other factors such as salinity should also be investigated.

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