Flow Behavior of Enhanced Oil Recovery Alcoflood Polymers

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Received 9 July 2001; accepted 9 November 2001

ABSTRACT: Flow behavior in terms of shear stress and viscosity versus shear rate is investigated for aqueous solutions of Alcoflood polymer materials. Rheostress RS100 is employed for operating, measuring, and analyzing this experimental investigation. Polymer concentration in the range of 100–10,000 ppm was covered. Fitting analysis is carried out for all the examined polymer solutions. Casson and Ostwald-de-Waele correlations can be employed for predicting flow behavior, depending upon polymer type. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 85: 2896–2904, 2002

Key words: shear; stress; viscosity; rheology

INTRODUCTION

The application of Alcoflood polymers in enhanced oil recovery is very necessary to keep the crude oil production rate at the required economical level after conventional methods have been exhausted. The enhanced oil recovery process is aiming for almost half of the original amount of the crude oil, which could not be produced by the conventional techniques.

Alcoflood polymer provides excellent handling characteristics and solubility to enhance injection properties through reservoir permeability. In several enhanced oil recovery applications, polymers are utilized as thickeners to alter the rheology of the continuous phase to improve mobility ratio and sweep efficiency and to increase recovery and oil production rates.[1] Alcoflood polymer, water-soluble powder, is widely applied in enhanced oil recovery to extract some of remained oil in the well or to push surfactant solutions in the tertiary oil recovery stage. In general, polymer characteristics should meet the service conditions in the oil reservoir. These conditions require polymer to provide complete solubility, no branches to reduce effect of shear, high viscosity of low solution concentration, and good mobility control.[2]

The presence of an immiscible crude oil in aqueous polymer solution forms an emulsion. Numerous experimental investigations were carried out on the rheological behavior of emulsions in which the continuous phase is Newtonian fluid.[3–6] Few studies on emulsion rheological behavior were found in which the continuous phase is a non-Newtonian polymeric solution.[7–8] However, many more investigations are reported on the flow behavior in the presence of solid particles in polymer emulsion.[9–17] The first part of this

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Journal of Applied Polymer Science, Vol. 85, 2896–2904 (2002)

Table I Polymer Specifications

	AF1235	AF1275	AF1285
Bulk density, g/cm^3	0.8	0.8	0.8
Intrinsic viscosity	12	20	24
Viscosity of 0.1% solution @ 20°C, CP	18	34	37
pH of 1% solution	7.0	7.0	7.0

comprehensive study focused on the flow behavior of aqueous solutions of Alcoflood polymer materials, which were used extensively in the enhanced oil recovery. Three different types of Alcoflood polymers with a wide range of concentrations are investigated by using a Rheostress RS100 rheometer. Alcoflood polymer is a high molecular weight polyacrylamide copolymer of granular powder form.

Several rheological investigations were carried out on polyacrylamide aqueous solutions.[18–30] Li and McCarthy[18] investigated the flow behavior of polyacrylamide aqueous solution through pipeline, employing nuclear magnetic resonance imaging. Ghoniem et al.[19] and Chang and Darby[20] reported mechanical degradation of polyacrylamide aqueous solution. On the other hand, Chauveteau[21] and Durst et al.[22] studied the flow behavior of polyacrylamide aqueous solution in porous media. They reported a significant pressure drop compared to Newtonian solutions. Dupuis et al.[23] studied the rheological behavior of polyacrylamide in aqueous solution of glycerol and water. They concluded that the viscosity of this solution showed a time effect with strong instability followed by steady-state behavior. Ait-Kadi et al.[24] investigated the effect of salt on the viscoelastic behavior of the polyacrylamide solution. They found that the salt provided a stability effect on the solution viscosity. Shin and Cho[25] studied the effect of temperature on the rheological behavior of polyacrylamide aqueous solution. They concluded that the viscosity showed temperature dependence at low shear rates and temperature independence at high shear rate. Several techniques based on continuum theories,[26] mechanical models,[27] and molecular theories[28–30] were employed to explain some of the reported observations. However, it is important to study the flow behavior of the actual commercial Alcoflood polymer, which is widely employed in the enhanced oil recovery techniques. Knowledge of the Alcoflood polymer flow behavior is necessary for the design, selection, and operation of the equipment employed in mixing, storage, pumping, and transportation of Alcoflood polymer solution.

EXPERIMENTAL

Alcoflood material is a high molecular weight polyacrylamide copolymer supplied by Ciba Specialty Chemicals (Bradford, West Yorks, U.K.). Three different materials of Alcoflood are investigated for flow behavior study. These materials, in order, are Alcoflood 1235 (AF1235), Alcoflood 1275 (AF1275), and Alcoflood 1285 (AF1285). AF 1235 is employed for low-medium permeability reservoirs; however, the other two types are designed for high permeability reservoirs. Alcoflood materials, white water-soluble, are supplied in a granular powder form. Table I shows polymer specifications for AF1235, AF1275, and AF1285.

The tested solutions are prepared by adding a certain weight of Alcoflood polymer material to 1 L of warm running water. Enough time was given to achieve complete polymer dissolution without external mixing to avoid any mechanical degradation on the polymer network. This study covers a wide range of various concentrations of 100–10,000 ppm (0.01–1%) for the three Alcoflood polymer materials.

Rheostress RS100 rheometer from Haake was employed to study the flow behavior of various concentrations of Alcoflood solutions. All measurements were carried out at a room temperature of 22°C. A water bath was employed to control the applied temperature in the RS100 system. The RS100 offers several operating modes of controlled rate (CR) mode, controlled stress (CS) mode, and oscillation (OSC) mode. One of the important specifications of RS100 is its capability to apply shear stress under CS mode with extremely low inertia. The drive shaft of the RS100 is centered by an air bearing to apply the specified stress on the tested sample without any friction. RS100 analyzes the resulting deformation of the

Table II Cone Specifications

Cone diameter, mm	35
Cone tip gap, mm	0.137
Cone angle, degree	4

examined material with a digital encoder, which can process a million impulses/revolution. This high resolution allows us to measure small shear rates, strains, and yield stress values. The operating mode in RS100 can be easily switched between CR and CS modes, and it can also apply oscillating stress and frequency sweep. Cone-plate sensor is used; cone is positioned on the plate by a controlled variable lift speed. Table II shows all cone specifications. A Haake software system is utilized in all operations, measurements, and data analysis of flow behavior investigation.

RESULTS AND DISCUSSION

The flow properties of AF1235, AF1275, and AF1285 Alcoflood polymers are investigated in terms of shear stress–shear rate and viscosity–shear rate behaviors. Rheostress RS100 is employed in all the experimental measurements. A wide range of polymer concentrations in the range of 100–10,000 ppm were covered. A polymer solution of a 1-cm^3 sample was placed first on the plate and the cone was then driven automatically to the right position. After the measurement data were collected, the RS100 software package was utilized to carry out all the data analysis required.

Figure 1 shows the rheogram behavior of shear stress, in Pa, versus shear rate, in s^{-1}, for AF1235 over the concentration range of 500–10,000 ppm. These measurements covered four cycles of shear rate from 0.1 to 1000 s^{-1}. Figure 1 shows that the shear stress is a strong function of polymer concentration and shear rate. Shear stress gradually increases by increasing the shear rate and polymer concentration. The effect of polymer concentration is more pronounced at low shear rate than at higher shear rate. Figures 2 and 3 show the same rheogram behaviors for AF1275 and AF1285, respectively. Almost similar influence for shear rate and polymer concentration on shear stress can be concluded for AF1275 and AF1285. Rheostress RS100 software package was employed to complete the data analysis of all the experimental results. The purpose of this analysis is to predict the more relevant model that represents the rheogram behavior. From the investigation of this analysis, two models can be found to sufficiently fit all the measurements depending upon the Alcoflood polymer material. These models are Power-law and Casson[31] models, respectively.

$$\tau = m\gamma^n \quad (1)$$

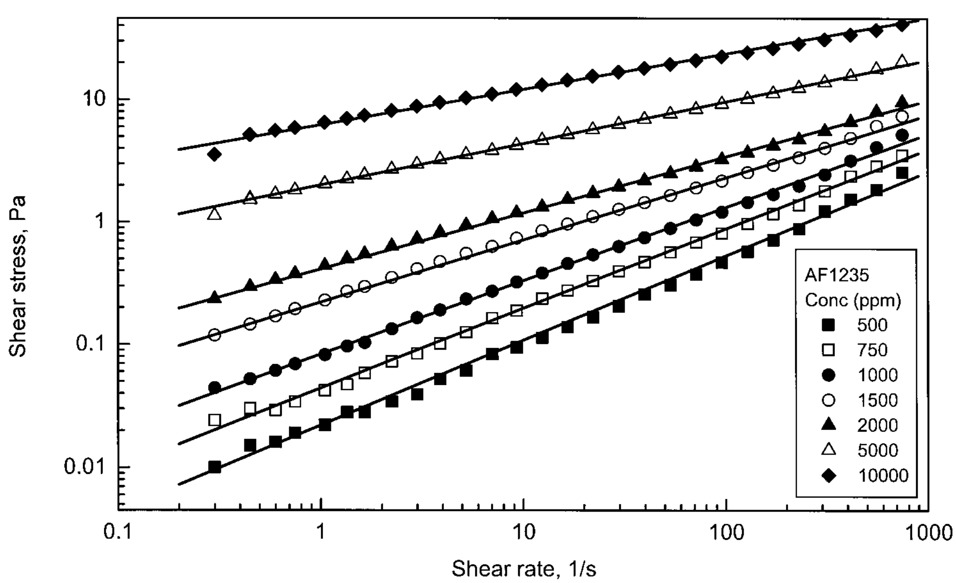

Figure 1 Rheogram behavior of AF1235.

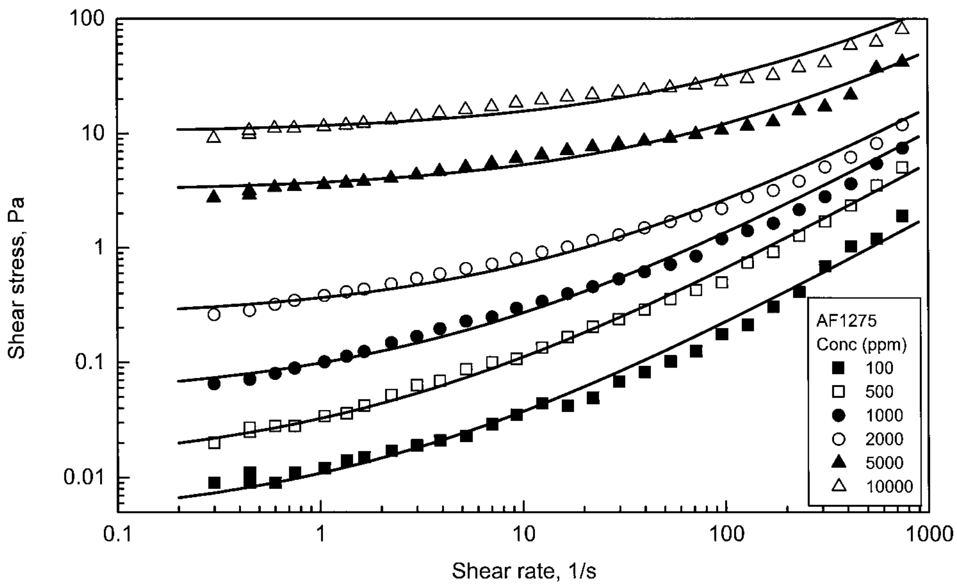

Figure 2 Rheogram behavior of AF1275.

$$\tau = [\tau_0^{0.5} + (\gamma\eta_c)^{0.5}]^2 \quad (2)$$

The Power-law model, eq. (1), fits very sufficiently the flow behavior for AF1235 over the range of concentration of 500–10,0000 ppm, whereas the Casson model of eq. (2) fits the flow behavior for AF1275 and AF1285 over the 100–10,000 ppm. The solid curves shown in Figures 1–3 are plots of the Power-law model (Fig. 1) and Casson model (Figs. 2–3). Tables III-V show the modeling analysis for AF1235, AF1275, and AF1285, respectively.

Table III shows the Power-law model parameters of m and n for AF1235. Flow behavior index, n, gradually decreases with polymer concentration, indicating strong shear thinning behavior for AF1235. The smaller the value of n, the greater is the degree of shear thinning. Table III shows that the flow consistency coefficient, m, for

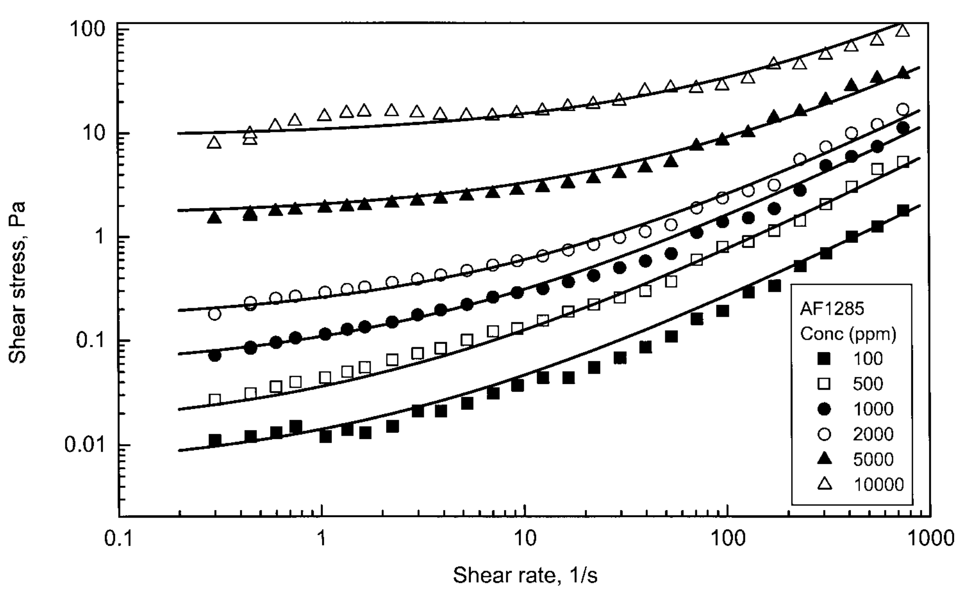

Figure 3 Rheogram behavior of AF1285.

Table III Modeling Analysis For AF1235 By Power-Law Model

	Parameters	
Concentration	m	n
500	0.022	0.69
750	0.044	0.65
1000	0.083	0.6
1500	0.22	0.51
2000	0.41	0.46
5000	2.0	0.34
10,000	6.2	0.29

the polymer solutions increases gradually with Alcoflood polymer concentration.

Figures 2–3 show that the Casson model (i.e., solid curves) fits very adequately the flow curves of AF1275 and AF1285 over the entire range of the examined shear rate. As can be observed from these figures that the Casson model predicts the flow behavior at low-shear (i.e., yield stress region) and at high-shear rate. Yield stress value, τ_0, for AF1275 increases gradually with polymer concentration from 0.012 to 8.7 Pa for the concentration range of 100–10,000 ppm. Similar behavior is reported for AF1285 with the yield stress range of 0.0055–9.2 Pa. The presence of yield stress indicates that a three-dimensional network is formed at no shear conditions. Under the effect of shear stress, the three-dimensional network is breakdown. Consequently, the flow behavior for these Alcoflood solutions exhibit shear thinning behavior which will be closely similar to the power-law model at high shear rate range.

Among the measurements that can be accomplished by the Rheostress RS100 is the viscosity value for all the examined polymer solutions. Figure 4 shows the flow behavior in terms of viscosity, mPas, versus shear rate, s^{-1}, for seven different concentrations of aqueous polymer solutions. This study covers a wide spectrum of concentrations in the range of 500–10,000 ppm at room temperature. Four cycles of shear rate were tested in the range of 0.1–1000 s^{-1}. All polymer aqueous solutions of AF1235 show non-Newtonian behavior over the tested shear rate. The apparent viscosity of all concentrations decreases gradually and steadily with shear rate. This strong shear thinning behavior that was observed for all the examined Alcoflood solutions is a typical behavior for polymer solutions in which viscosity response of polymer solution decreases by shear rate. Figure 4 shows that the viscosity of AF1235 is a strong function of polymer concentration as well; the higher concentration of polymer solution provides higher solution viscosity. Figures 5-6 display a similar behavior for AF1275 and AF1285, respectively. The rheogram's previous analysis can be utilized for further design calculation. This analysis provided that the Power-law model and Casson model are very relevant for predicting flow behavior, depending upon polymer type. The Power-law model, eq. (3), fits well the flow behavior of AF1235 polymer solution, whereas the Casson model, eq. (4), adequately fits the flow behavior for AF1275 and AF1285 polymer solutions:

$$\eta = m\gamma^{n-1} \tag{3}$$

$$\eta = [(\tau_0/\gamma)^{0.5} + (\eta_c)^{0.5})]^2 \tag{4}$$

It is important for this study to compare between the flow behavior of the three tested types of polymer material to find the similarities and differences in the performance of the polymer so-

Table IV Modeling Analysis For AF1275 By Casson Model

	Parameters	
Concentration	τ_0	η_c
100	0.012	0.0028
500	0.02	0.0059
1000	0.056	0.0083
2000	0.2	0.012
5000	3.2	0.029
10,000	8.7	0.043

Table V Modeling Analysis For AF1285 By Casson Model

	Parameters	
Concentration	τ_0	η_c
100	0.0055	0.002
500	0.013	0.0058
1000	0.051	0.011
2000	0.15	0.015
5000	1.6	0.031
10,000	9.2	0.08

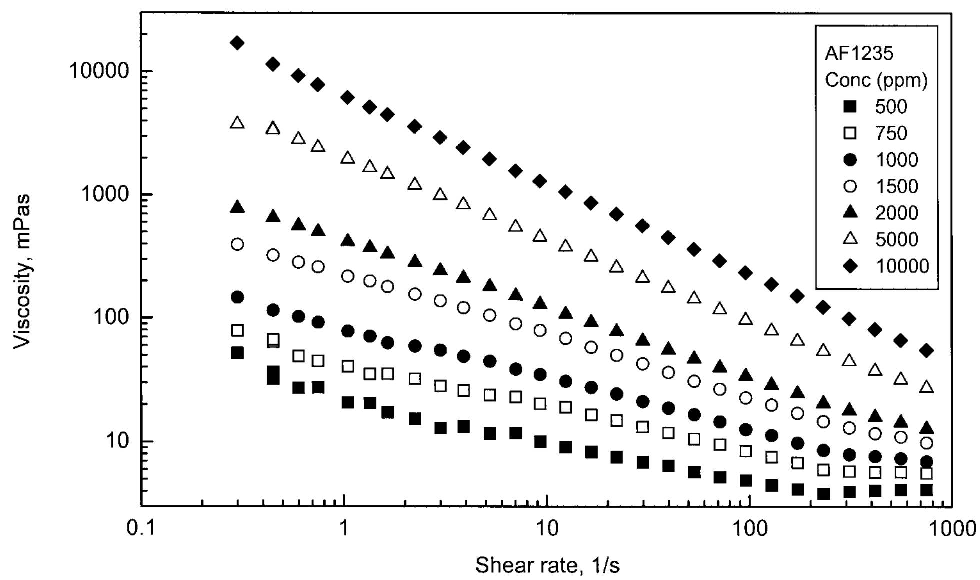

Figure 4 Apparent viscosity versus shear rate for different concentrations of AF1235.

lution. Figures 7-10 show the rheogram behavior of the three polymer solutions in terms of shear stress–shear rate relationship on a semilogarithmic scale for 100, 500, 1000, and 10,000 ppm, respectively. Figure 7, for 100 ppm polymer concentration, shows exactly similar rheogram behavior up to a shear rate value of 100 s^{-1} and insignificant differences up to 1000 s^{-1}. However, Figures 8-10 for polymer concentrations of 500, 1000, and 10,000 ppm show two distinct rheogram behaviors. The first performance covers the shear rate range of 0.0–100 s^{-1}, which displays an almost similar rheogram behavior, whereas the second distinct performance covers the shear rate range of 100-1000 s^{-1}, in which rheogram performance depends upon the polymer type. Figures 8–10, over the shear rate range of 100-1000 s^{-1}, show that the shear stress increases signifi-

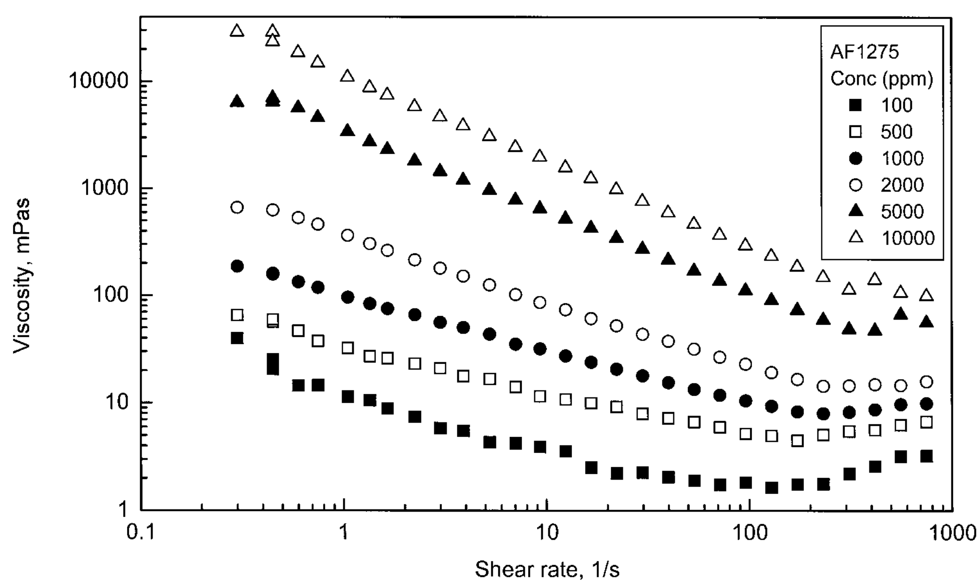

Figure 5 Viscosity–shear rate behavior for AF1275.

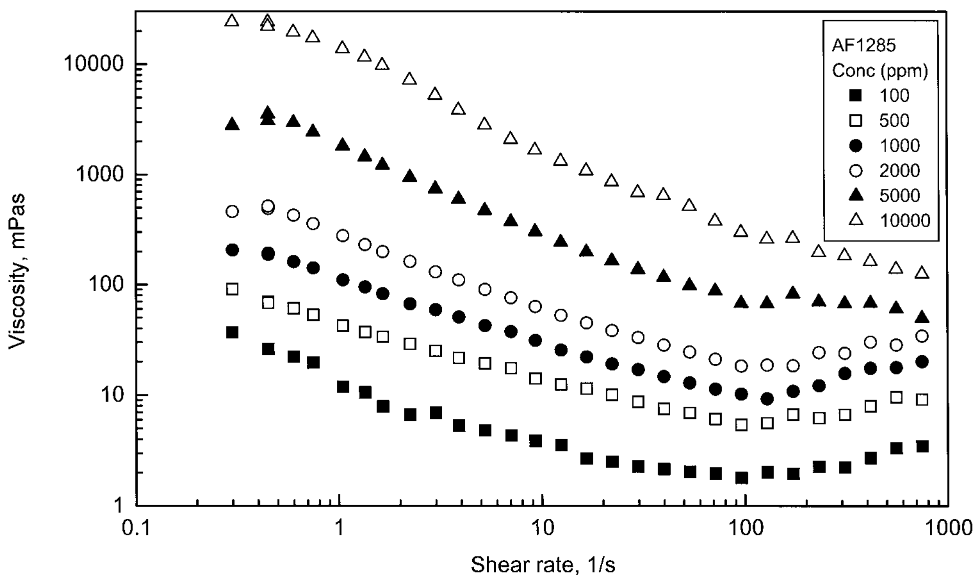

Figure 6 Viscosity–shear rate behavior for AF1285.

cantly in the order of AF1235, AF1275, and AF1285.

CONCLUSION

A rheological investigation in terms of shear stress–shear rate and viscosity–shear rate for three different types of Alcoflood polymer materials (AF1235, AF1275, and AF1285) is accomplished. This study covered a wide range (100–10,000 ppm) of Alcoflood polymer aqueous solutions. The following conclusions can be pointed out.

1. Shear stress is a strong function of polymer concentration and shear rate regardless of Alcoflood polymer type. Shear stress gradually increases by increasing polymer concentration and shear rate.

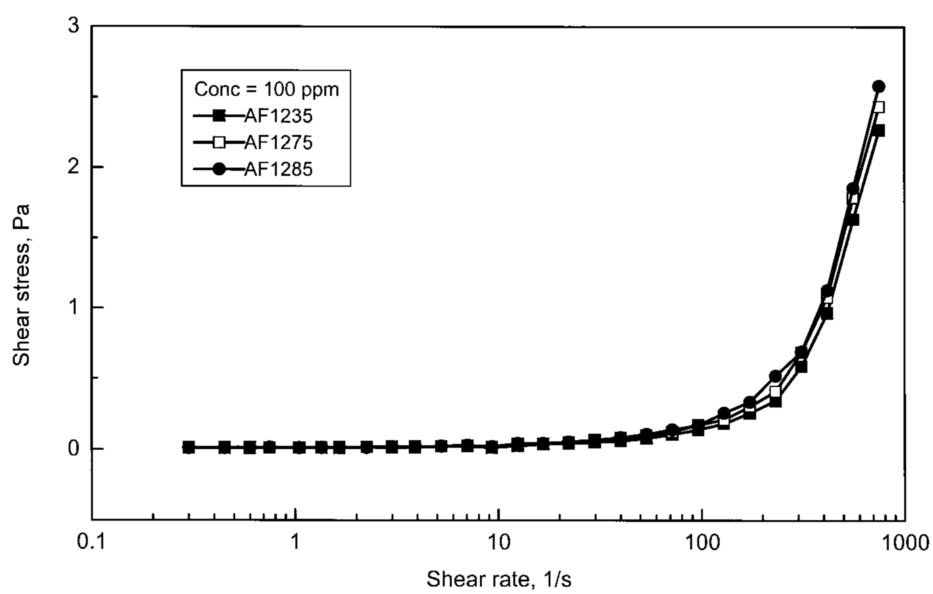

Figure 7 Effect of polymer type on rheogram behavior for 100 ppm.

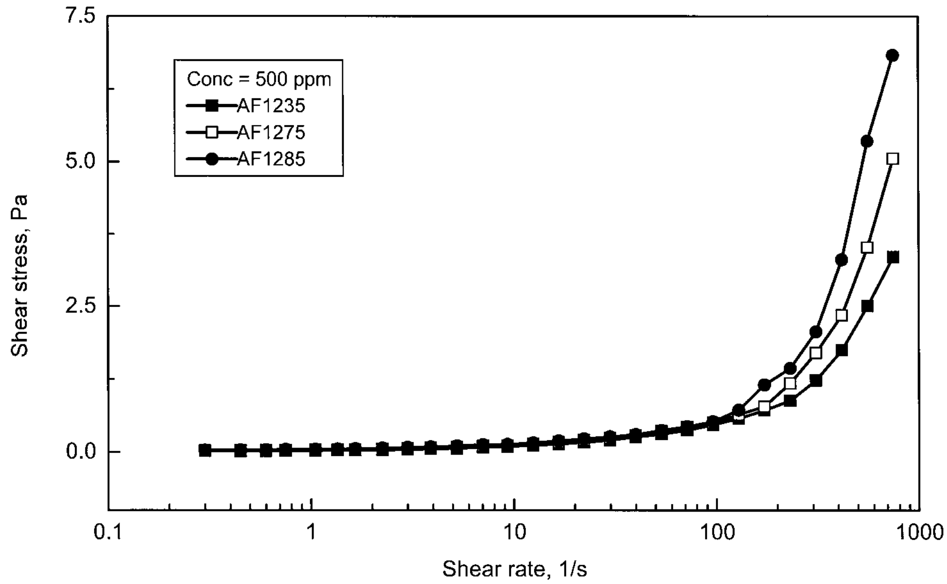

Figure 8 Effect of polymer type on rheogram behavior for 500 ppm.

2. The effect of polymer concentration is more pronounced at low shear rates.

3. Modeling analysis showed that two models of Power-law and Casson, based on Alcoflood polymer type, could be utilized to predict the flow behavior of Alcoflood aqueous solutions.

4. Power-law model fits well the AF1235 aqueous solution.

5. Casson model fits adequately the aqueous solutions of AF1275 and AF1285.

6. The apparent viscosity for all aqueous solutions of Alcoflood materials is a strong function of shear rate and polymer concentrations.

7. All Alcoflood polymer aqueous solutions of AF1235, AF1275, and AF1285 showed strong shear thinning non-Newtonian behavior over the entire examined shear rate. The apparent viscosity of all concentrations decreases gradually and steadily with shear rate.

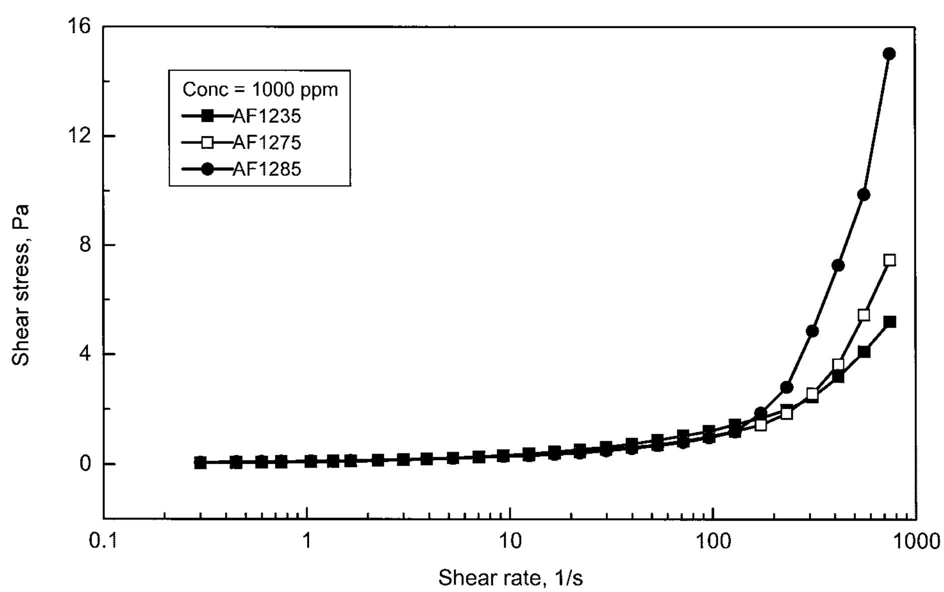

Figure 9 Effect of polymer type on rheogram behavior for 1000 ppm.

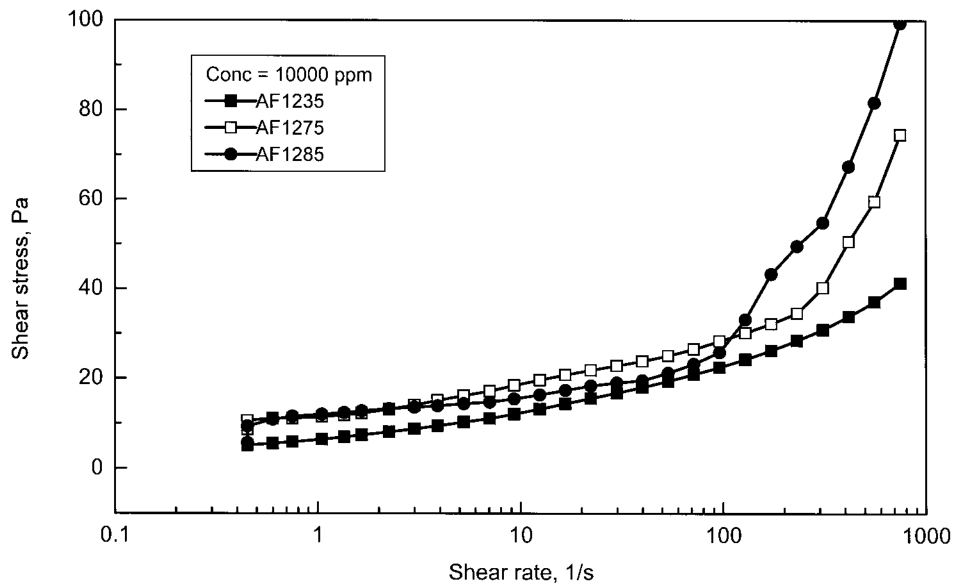

Figure 10 Effect of polymer type on rheogram behavior for 10,000 ppm.

8. Two distinct behaviors can be concluded from the rheogram comparison. The three Alcoflood materials provided almost similar behavior over the shear rate of 0.0–100 s^{-1}. However, over the shear rate of 100-1000 s^{-1}, the rheogram behavior is Alcoflood-type dependent. The shear stress increases significantly in the order of AF1235, AF1275, and AF1285.

The financial support granted to Dr. M. Ghannam from the United Arab Emirates University under Grant No. 15-7-11/02 is gratefully acknowledged. The authors are grateful to Ciba Specialty Chemicals (Bradford, West Yorks, U.K.) for supplying the required Alcoflood polymers.

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