

Optimizing Fluid Rheology for Enhanced Oil Recovery Applications: A Case Study



RHEOLOGY AND VISCOSITY

Introduction

Enhanced Oil Recovery (EOR) is gaining increasing attention due to the shortage of current oil resources and difficulties in finding a new oil field. With traditional methods, only about 20-40% of oil is extracted from a newly drilled oil reservoir leaving 60-80% oil in the reservoir. With EOR technology an additional 20% of oil can be obtained from the reservoir. Polymers, especially surfactant and hydrogel polymers play an important role in the application of EOR technology [1]. Polymer flooding is a technically proven technology for EOR applications, where the injection of a solution into porous rock is performed in order to recover residual oil, with fluids having significant viscoelastic characteristics shown to improve displacement efficiency and recovery yields compared with conventional Newtonian fluids [2-4].

The Institute of Petroleum Engineering at TU Clausthal in Germany have been working on a project to better understand the rheological behaviour of such fluids, under conditions likely to be encountered during the oil recovery process, with support from Malvern Instruments.

To date, this study has focused primarily on EOR polymer systems, which tend to be high molecular weight polymers including hydrolyzed polyacrylamides and biopolymers. Due to their high molecular weights and solution concentration, these polymer solutions exhibit a combination of viscous and elastic responses – or viscoelasticity and have a non-Newtonian shear rate-dependent viscosity. They can both store energy (an elastic response) and dissipate energy (viscous response), depending on the rate or time of deformation. They can also show remarkable resistance to stretching (high extensional viscosity) compared to that observed under shear. This latter aspect is important since to traverse pores via narrow connecting channels, the fluid must accelerate and then decelerate to maintain a constant volumetric flow rate. This generates stretching or extensional

forces along the flow axis, while at the same time the fluid close to the walls is subjected to shear forces.

To explore this complex flow behaviour requires the use of complementary measurement techniques and test protocols. For example, a rotational rheometer can give information about the flow properties of a polymer solution by measuring the shear viscosity as a function of shear rate and also the linear viscoelastic behaviour of the material under non-flow conditions using oscillatory testing (small amplitude oscillatory shear). However, rotational rheometry can also be used to study the non-linear viscoelastic behaviour of a material under flow by measuring the normal stresses (from force acting on the upper geometry) generated under rotational shear. These normal stresses result from flow induced anisotropy – for example polymer coils can become ellipsoidal in a shear field and can stretch out at higher deformation rates due to the curved flow path generated in a rotational rheometer. This generates a restoring force or tension in the streamlines which translates to a normal stress acting on the upper geometry [5-7].

In this case study we present elements of the work carried out by Rafael Hincapie as part of his PhD project at TU Clausthal to better understand how viscoelastic properties of EOR polymers influence oil recovery performance. We show how non-linear viscoelastic measurements made on a rotational rheometer can be used to help explain the behavior of viscoelastic polymers in the porous media and how this behaviour is influenced by environmental conditions [8].

Materials and Methods

In this study, HPAM (Hydrolyzed Polyacrylamide) solutions were characterised using a Kinexus rotational rheometer and a microfluidic rheometer (eVROC), employing a microfluidic channel with a contraction zone to estimate the extensional viscosity under geometric conditions similar to those encountered in the reservoir [8]. Effects of concentration, temperature and hardness of reservoir brines were evaluated. In addition, Glass-Silicon-Glass micromodels (GSG) based on CT scan of real core samples were used as Core analogues to assess the pressure requirements for pushing EOR fluids through a rock section at different flow rates [9]. From these pressure measurements it was also possible to estimate apparent viscosity in-situ based on Darcy's diffusion law, for comparison with measured rheological data [10].

Findings and Discussion

Figure 1 below shows shear viscosity data plotted against shear rate data for a HPAM polymer solution (MW \approx 26 MDa, Conc = 2000 ppm) in brine, measured using the Kinexus rotational rheometer and calculated using Darcy's law based on flow through the GSG micromodel at different flow rates. Good agreement was found between the GSG micromodel data and the Kinexus data in the mid shear range, demonstrating the validity of Darcy's law for estimating viscosity in-situ for a porous structure. Discrepancies were, however, observed compared with rotational rheometry at lower shear rates where higher viscosities were measured and at higher shear rates, where the onset of shear thickening was observed. This apparent shear thickening behaviour has been reported by other authors based on similar flow experiments in porous media [11]. The fact such 'thickening behaviour' is not observed in rotational rheometer measurements, however, suggests that this phenomenon is related to the geometric configuration of the rock and its series of connected pores and channels.

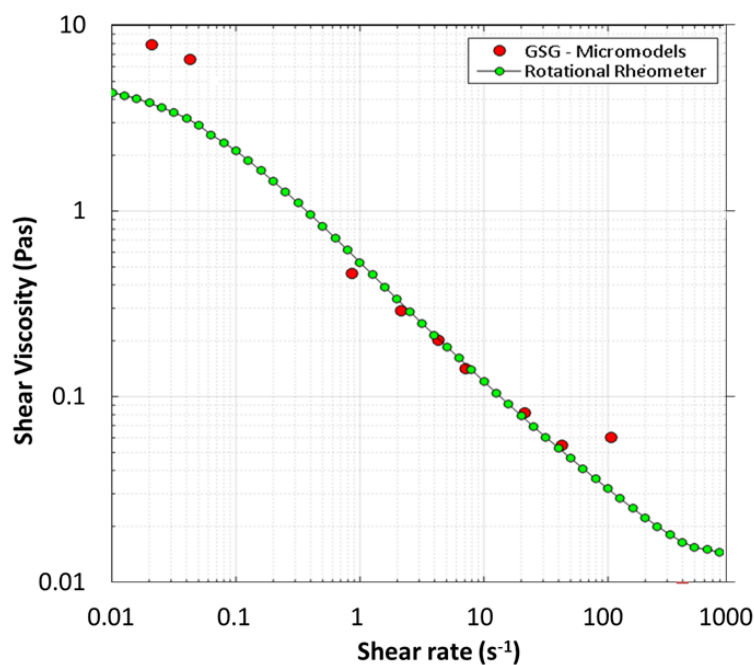


Figure 1 - Steady shear viscosity measured using a Kinexus rheometer compared with apparent viscosity measurements obtained with GSG micromodels for HPAM polymer solution at 2000 ppm in 4 g/l brine, 22°C

As discussed previously such a geometric arrangement can give rise to extensional stresses as a result of acceleration/deceleration of the fluid through the arrangement of narrow channels and pores, and this can be highly significant for high molecular weight polymers. Figure 2 shows a plot of first normal stress difference and shear stress measured with cone and plate configuration as a function of shear rate. As expected the shear stress increases with increasing

shear rate but shows a non-linear profile indicating non-Newtonian-shear thinning behaviour, as confirmed in Figure 1. The normal stress (N_1) profile is quite different, however; N_1 remains relatively constant up to a shear rate of approximately 50 s^{-1} but then shows a continual increase above this, indicative of tension in the polymer chains. The onset of this increase occurs at a similar shear rate to that where apparent shear thickening is observed in the GSG micromodel, suggesting that the extra pressure required to maintain flow of the EOR fluid in the pore structure above 50 s^{-1} is due to elastic effects (stretching of the polymer) and not an increase in the shear viscosity. Similar conclusions have been reached by another group using Malvern rheometers [12].

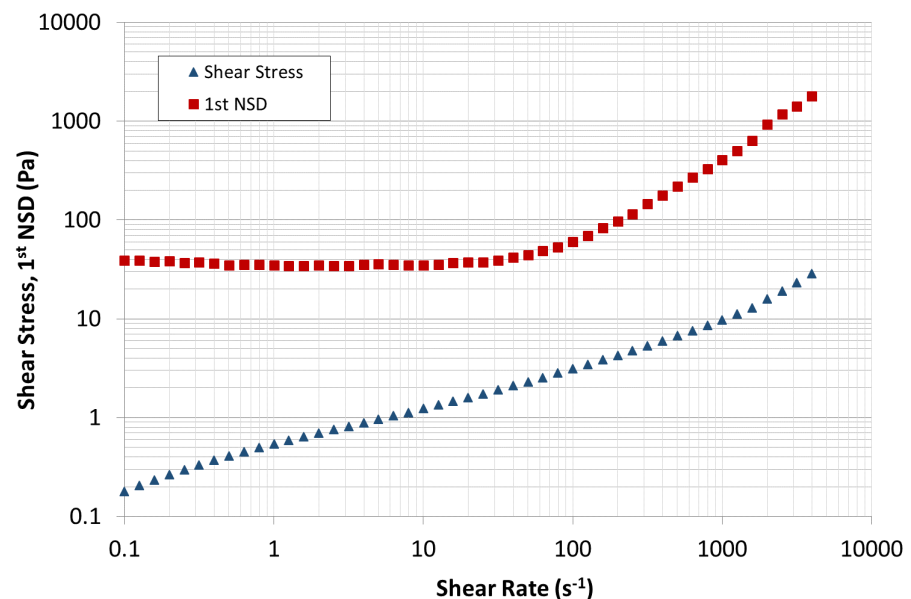


Figure 2 - Steady shear stress and first normal stress difference measured using a Kinexus rheometer for HPAM polymer solution at 2000 ppm in 4 g/l Brine, 22°C

Such conclusions are supported by measurements made using the eVROC microfluidic rheometer where extensional stresses can be measured directly under conditions similar to those encountered in the rock structure. Normal stress measurements made on the Kinexus rheometer and extensional stress measurements made using the eVROC are plotted together in Figure 3. Although the stress magnitudes are different, the two measurements are clearly related with the observed increase in extensional and normal stresses occurring at similar deformation rates, be it extension or shear. For the purposes of comparison, the magnitude of the shear rate can be considered equivalent to $\sqrt{3}$ x extension rate as used to calculate the so-called Trouton ratio (ratio of extensional viscosity to shear viscosity) [5,6].

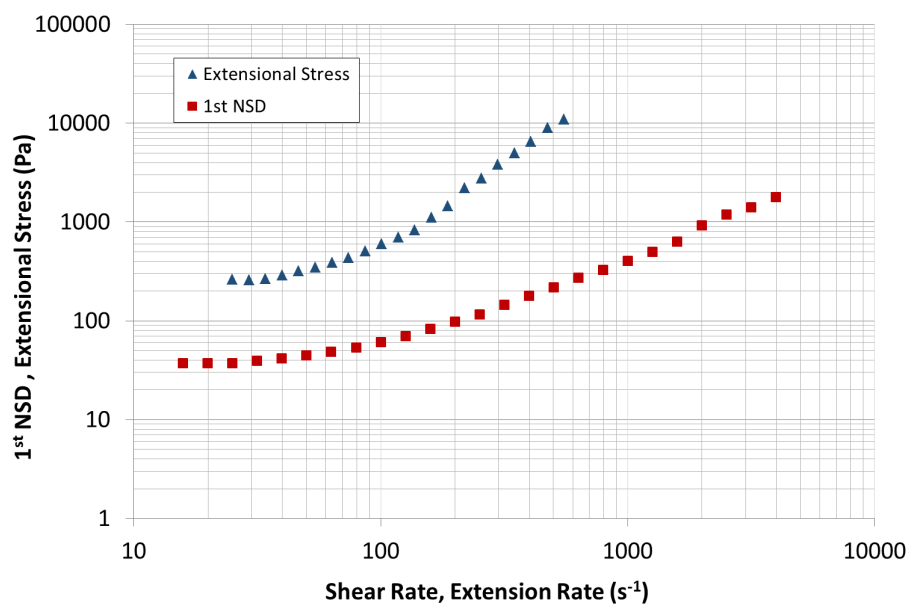


Figure 3 - First normal stress difference measured using a Kinexus rheometer compared with extensional stress measured using a microfluidic extensional rheometer for HPAM polymer solution at 2000 ppm in 4 g/l brine, 22°C

N_1 comparisons for different EOR polymer solutions showed a strong dependence on polymer concentration, salinity and whether polymers had been pre-sheared or not (data not shown). This is most likely related to the volume occupied by the polymer in solution, which influences viscoelastic behaviour and is sensitive to factors such as solvent quality, molecular weight and concentration [13].

Work is ongoing to further elaborate on these findings with additional Malvern techniques such as Microrheology (Zetasizer Nano) being employed to investigate the short-time dynamics and relaxation behavior of these polymer systems, and possibly Gel Permeation Chromatography (Omnisec) to investigate scission of polymer chains during the polymer injection process.

Conclusions

Non-linear viscoelastic information (viscoelasticity induced by flow) of polymer utilised for EOR applications can be determined from normal stress measurements using a rotational rheometer. For a number of HPAM solutions measured in this study, a large increase in normal stress was observed above a critical shear rate of approx. 50 s^{-1} . This corresponds with an observed increase in the pressure required to maintain flow at an equivalent shear rate in a rock core micromodel structure, a phenomena that has previously been attributed to shear thickening (viscosity increase) in the pore structure. Normal stress data, however, indicates that the pressure increase is a result of enhanced elasticity due to stretching of polymer chains in the flow field and not viscosity. Such conclusions are supported by extensional viscosity measurements made with a microfluidic extensional rheometer, which show that the increase in normal stress coincides with an increase in extensional stresses at similar deformation rates. Furthermore, normal stress comparisons for different polymer solutions showed a strong dependence on polymer concentration, salinity and whether polymers had been subjected to a pre-shear, suggesting that the performance of polymer use for EOR in the reservoirs is strongly dependent on environmental conditions.

References

- [1] Z. Abidin et al; Procedia Chemistry 4 (2012) 11 – 16
- [2] D. Wang, J. Cheng, W. Gong, Q. Yang, Q. Li and F. Chen; Viscous-Elastic Polymer Can Increase Microscale Displacement Efficiency in Cores, SPE J.,2000, SPE63227
- [3] D. Wang, H. Xia, S. Yang and G. Wang; The Influence of Visco-elasticity on Micro Forces and Displacement Efficiency in Pores, Cores and in the field, SPE J., 2010, 127453
- [4] Wang, D., Wang, G., Wu, W., Xia, H., and Yin, H; The Influence of Viscoelasticity on Displacement Efficiency-from Micro- to Macroscale. Paper SPE-109016-MS presented at SPE Annual Technical Conference and Exhibition, Anaheim, California, U.S.A. 11-14 November 2007
- [5] Barnes, HA, Hutton, JF and Walters, K; An introduction to rheology. Elsevier (1989). ISBN: 0-444-87469-0
- [6] Shaw MT; Introduction to Polymer Rheology. Wiley (2012)
- [7] Evaluating non-linear viscoelastic effects using normal force measurements –Malvern Instruments application note - [http://www.malvern.com/en/support/resource-center/application notes/AN150410EvaluatViscoEffects.aspx](http://www.malvern.com/en/support/resource-center/application%20notes/AN150410EvaluatViscoEffects.aspx)

[8] Hincapie, R.E. Duffy, J. O'Grady, C and Ganzer, L; An Approach to Determine Polymer Viscoelasticity under Flow through Porous Media by Combining Complementary Rheological Techniques, SPE J., 2015, SPE174689

[9] Wegner, Jonas; Investigation of Polymer Enhanced Oil Recovery (EOR) in Microfluidic Devices that Resemble Porous Media Dissertation. TU Clausthal, Germany 2015

[10] Ganzer, L, Wegner, J and Buchebner, M. Benefits and Opportunities of a "Rock-on-a-Chip" Approach to Access New Oil - Oil Gas-European Magazine 39, p 43-47, 2014.

[11] Delshad, M, Kim, DH, Magbagbeola OA, Huh C, Pope, GA, and Tarahhom, F; Mechanistic Interpretation and Utilization of Viscoelastic Behaviour of Polymer Solutions for Improved Polymer-Flood Efficiency. Paper SPE-113620-MS presented at SPE/DOE Symposium on Improved Oil Recovery 20-23 April 2008 Tulsa, Oklahoma, USA.

[12] Clarke A, Howe AM, Mitchell J and Hawkes L; How Viscoelastic Polymer Flooding Enhances Displacement Efficiency, SPE J., 2015, SPE174654

[13] Measuring the rheology of polymer solutions – Malvern Instruments White Paper - <http://www.malvern.com/en/support/resourcecenter/Whitepapers/WP150324MeasRheologyPolymerSols.aspx>



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