Shear and Elongational Rheology of Partially Hydrolyzed Polyacrylamide Used for Enhanced Oil Recovery

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Abstract:
Rheological properties are one of the primary considerations in selecting a fluid for using in chemical flooding enhanced oil recovery (EOR) operations. In this work, the rheological behavior of partially hydrolyzed polyacrylamide (HPAM) used for EOR was characterized by different techniques like steady shear flow and uniaxial elongation in capillary breakup experiments. Particular attention was focused on the main parameters affecting flow behavior of solutions, such as polymer concentration, molecular weight and molecular weight distribution. The shear rate dependence of viscosity for HPAM solutions could be described by the Carreau model. Elastic model was used to fit the rheological results obtained by transient uniaxial extensional technique, which enabled to evaluate relaxation time. The results indicated that the elasticity of HPAM solutions was dominated by molecular weight. Shear viscosity at higher shear rates was mainly influenced by polymer concentration, which was not an important factor determining relaxation time. For HPAM solutions, increasing of molecular weight distribution led to a decrease in shear viscosity, and vice versa for elongational viscosity and relaxation time. In addition, it was found that there was direct proportional relationship between first normal stress difference and elongational viscosity.

Zusammenfassung:
Die rheologischen Eigenschaften zählen zu den wichtigsten Größen bei der Auswahl von Fluiden für die Ölgewinnung mit Hilfe der Methode der chemischen Flutung (EOR). In dieser Arbeit wurde das rheologische Verhalten von partiell hydrolysierten Polyacrylamiden (HPAM) für die EOR mit Hilfe unterschiedlicher Methoden wie stationärer Scherströmung und Dehnung unter uniaxialer Belastung in dem sogenannten „capillary breakup experiment“ untersucht. Ein besonderer Augenmerk wurde auf die wesentlichen Parameter gelegt, die das Fließverhalten dieser Lösungen beeinflussen, z. B. die Polymerkonzentration, das Molekulargewicht und die Molekulargewichtsverteilung. Die Abhängigkeit der Viskosität von der Schergeschwindigkeit für die HPAM-Lösungen wurde durch das Carreau-Modell beschrieben. Ein elastisches Modell wurde herangezogen, um die rheologischen Ergebnisse, die mit Hilfe von zeitabhängigen Dehnmessungen unter uniaxialer Belastung gewonnen wurden, anzupassen. Daraus konnte die Relaxationszeit bestimmt werden. Die Ergebnisse belegten, dass die Elastizität der HPAM-Lösungen vom Molekulargewicht bestimmt wird. Die Scherviskosität bei höheren Schergeschwindigkeiten wird hauptsächlich von der Polymerkonzentration beeinflusst, die keinen wesentlichen Faktor bei der Bestimmung der Relaxationszeit darstellte. Bei den HPAM-Lösungen führte eine Erhöhung der Molekulargewichtsverteilung zu einer Reduktion der Scherviskosität, und umgekehrt zu einer Erhöhung der Dehnviskosität und Relaxationszeit. Darüber hinaus wurde herausgefunden, dass eine direkte Proportionalität zwischen der ersten Normalspannungsdifferenz und der Dehnviskosität existiert.

Résumé:
Les propriétés rhéologiques sont une des principales caractéristiques qui sont prises en compte lors de la sélection d’un fluide utilisé durant les opérations de pompage du pétrole amélioré par voie chimique (EOR). Dans ce travail, le comportement rhéologique de polyacrylamide partiellement hydrogéné (HPAM) utilisé pour l’EOR a été caractérisé aux moyens de différentes techniques telles que l’écoulement de cisaillement continu et l’extension uni axiale conduite avec des expériences de scission de filament capillaire. Une attention particulière a été donnée aux principaux paramètres qui affectent l’écoulement des solutions, tels que la concentration en polymère, la masse moléculaire et la distribution en masse moléculaire. La dépendance de la viscosité des solutions de HPAM en fonction de la vitesse de cisaillement a pu être décrite par le modèle de Carreau. Un modèle élastique a été utilisé afin d’ajuster les résultats rhéologiques obtenus au moyen de la technique d’extension uni axiale transitoire qui permet l’obtention d’un temps de relaxation. Les résultats ont indiqué que l’élasticité des solutions de HPAM est dominée par la masse moléculaire. La viscosité de cisaillement aux grandes vitesses de déformation est principalement influencée par la concentration en polymère, qui n’est pas un facteur important pour le temps de relaxation. Pour les solutions de HPAM, l’augmentation de la distribution de la masse

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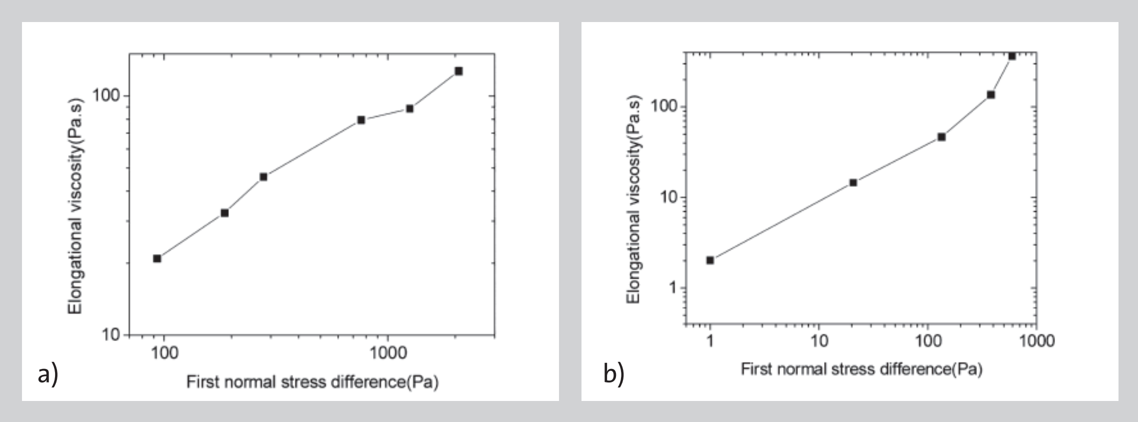

Figure 5: First normal stress difference versus elongational viscosity for solutions at (a) different polymer concentration and (b) different polymer molecular weight.

shear viscosity at higher shear rates, but a great increase in elongational viscosity and relaxation time. This result indicates that the HPAM with high molecular weights is very sensitive to shear rates, and which leads to its lower viscosity at higher shear rates. For higher molecular weight polymer, as the time acted upon by an external force is short, the deformation of viscous flow is small so the elastic deformation is great, which gives rise to greater elongational viscosity and relaxation time.

The stability of the system decreases with the increase in MWD, which results in the decrease of zero shear viscosity. The increase of viscosity at high shear rates should be attributed to the secondary flow resulted from the high elasticity of the system. CaBER experiment reacts very sensitive to the longest relaxation time of the high-molecular edge of the MWD and tiny amounts of high-molecular species can lead to a pronounced influence on the elongational behavior [28], and consequently the relaxation time and elongational viscosity increase with an increase in MWD. All in all, the result that different factors have different effects on the rheology in extensional and shear flow is attributed to the difference between extensional and shear flow, which is that there is more alignment or stretch in the extensional flow than in the shear flow and no rotation in the extensional flow.

In addition, it can be found from Table 3 that the change of the non-linear elastic parameters N_1 and $\eta_{app}(\epsilon)$ followed the same rule. The N_1 at shear rate 650 s^{-1} versus $\eta_{app}(\epsilon)$ at strain 6.5 is plotted in Figure 5. It shows that there is direct proportional relationship between first normal stress difference and elongational viscosity. The first normal stress difference comes into being only when the micro structure of the liquid becomes anisotropy during the flow, the normal stress component leads to a stretching. The direction of deformation resulted from the first normal stress difference in shear flow and the elongational stress in enlogational flow is same so that the first normal stress difference can be correlated to the elongational viscosity.

4 SUMMARY

The shear rate dependence of viscosity for HPAM solutions could be described accurately by the Carreau model. The elastic model could be used to fit the rheological results obtained by transient uniaxial extensional technique, which enabled to evaluate relaxation time of HPAM solutions. Also it was seem, that the elasticity was dominated by molecular weight. Shear viscosity at higher shear rate was mainly influenced by polymer concentration, but which was not an important factor determining relaxation time. Increasing of molecular weight distribution led to a decrease in shear viscosity, but an increase in elongational viscosity and relaxation time. There was direct proportional relationship between first normal stress difference and elongational viscosity. These results should be beneficial to designing the project, enriching the basic theory of polymer flooding and enhancing the oil displacement efficiency.

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