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A Comprehensive Combination of Apparent and Shear Viscoelastic Data during Polymer Flooding for EOR Evaluations

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Abstract

We present a comprehensive workflow to obtain the best insights into the viscoelastic behavior of polymers. Viscoelasticity is depicted in most cases by the current commercially available polymers used for EOR applications. The phenomenon is debated to be one of the reasons for additional oil recovery during polymer flooding applications. It is somehow accepted that polymer increases volumetric sweep efficiency owing to improved mobility ratio. Recently researches have explained that flooding polymers in porous media with elastic characteristics could recover additional oil, due to the improved microscale oil displacement (pore-scale). This study focuses on the analysis of polymer viscoelasticity based on single-phase core, sand-pack and capillary tube (CT) experiments coupled with their detailed rheological characterization, in order to evaluate polymer behavior in porous media. A combination of hydrolyzed polyacrylamides (HPAM) polymers as well as a bio polymer is presented throughout this evaluation. The evaluation of the data is addressed on the basis of pressure drop across the pores, separating the shear associated pressure by the extensional thickening associated pressure. Apart from that, viscoelastic dependence of the converging-diverging geometry has been experimented. Based on the observed behavior through porous media, HPAM polymers are compared with bio polymers. Moreover, the behavior of solutions with induced mechanical degradation (pre-sheared) is compared with non-sheared solutions. Similarly, concentrations with different polymer solutions are evaluated. The results obtained in this work allow for additional understanding of polymer solutions behavior in flooding applications. Furthermore The results support the definition of optimized workflows to assess their behavior under flow through porous media. Finally this evaluation helps to describe the parameter that defines polymer viscoelastic properties.

Keywords

Viscoelasticity, Mechanical Degradation, Elongational Viscosity, Weissenberg Number

1. Introduction

Among chemical enhanced oil recovery (EOR) methods, polymer flooding is the most widely used due to its simplicity and low cost. Polymers are used to increase viscosity of aqueous phase which improves mobility ratio and form a uniform flood front to displace oil [1], [2]. It has been as a technically and commercially proven technology and it is considered as one of the most mature chemical flooding methods. Polymer rheological behaviour through porous media affects sweep efficiency and injectivity during flooding process.

Many features of polymer flow through porous media and its impact on oil recovery are somehow known, but there are some technical challenges to be addressed. For instance, shear rate dependent polymer rheology in porous media. Polymer rheology is controlled through shear force exerted by wall of pores while flowing through porous media [3]. Viscoelastic polymers exhibit shear-thinning behavior during rotational rheometry experiments whereas, when flowing through porous media the same polymer solution depicts shear thickening behavior-at a certain medium/high shear rates [4] [5] [6]. Core flood experiments have confirmed apparent viscosity dependence on shear rate [6], [7]. Converging-diverging geometry due to pore size distribution cause polymer stretching and contraction, which results into shear thickening depending upon polymer relaxation time [8], [9]. Viscoelastic polymer behavior can be defined and is often analyzed by flow through media [6], [8] or by oscillatory rheology measurements [10] [11] [12] [13]. Different studies focusing on shear thinning and thickening properties have been presented. For instance, comparing the pressure drop behaviour against interstitial velocity (porosity, ϕ x superficial velocity, u) as reported by Sobti *et al.* [11], Heemskerk *et al.* [14], Hincapie [15], Kaur *et al.* [16]. Numerous models to calculate shear rate as function injection rates have been proposed and analyzed in the literature [7], [17] [18] [19]. In addition, shear rate experienced by a polymer while flowing through a capillary tube has been studied by Wei *et al.* [12] Furthermore, apparent viscosity in porous media (core plugs) has been calculated in literature using Darcy's formula [7].

This study focuses on the analysis of polymers based on single-phase core, sand-pack and capillary tube (CT) experiments coupled with their rheological behavior characterization, in order to evaluate and predict polymer behavior in porous media. Impact of polymer concentration, pre-shearing conditions and different type of polymers on polymer viscoelasticity in porous media is also emphasized considering various approaches. Elongation dominated excessive pressure drop is calculated by comparing total pressure drop happening in core flood and pressure drop accounting the rheometer viscosity. This investigation contributes to understand the viscoelastic flow dynamics of polymer in reservoir. Multiple approaches have been utilized to understand viscoelastic response of injected fluid, as viscoelasticity of fluid can recover more oil. Moreover this study endorses the existence and measurement of elongation dominated flow in porous media.

2. Material and Methods

A descriptive summary of materials and methods considered during this study can be seen from Figure 1.

2.1. Brine and Polymers

Brine with Total Dissolved Solids (TDS) of 4.0 g/l is used as make-up water for diluted polymer solutions. Brine composition is described in Table 1. Brine was filtered through 0.2 μm filter size by applying 2.0 Bar of Nitrogen gas pressure in order to avoid any undissolved component.

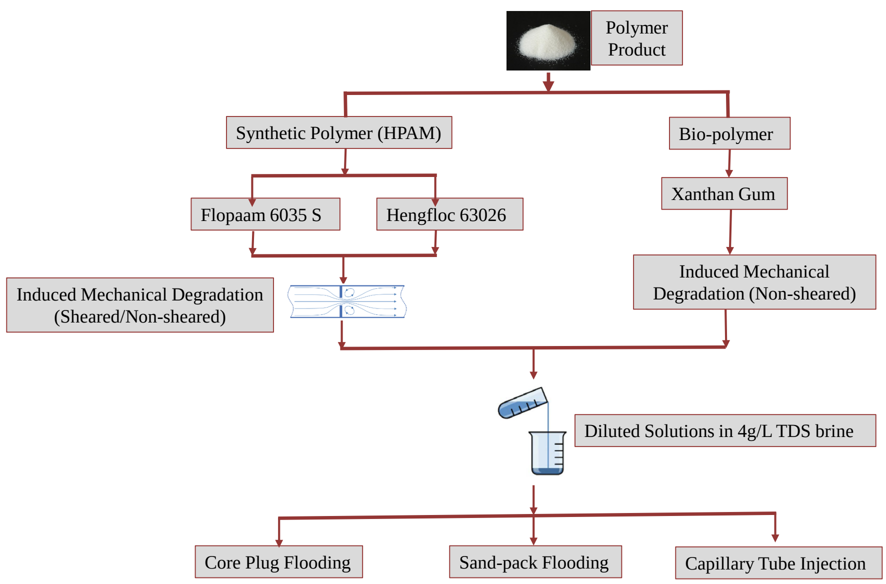


Figure 1. Descriptive flow chart of materials and methods adopted during this study.

Table 1. Brine compositions used during the discussed experiments.

Components	(g/L) 4.0 TDS
KCl	1.10411
$CaCl_2 \cdot 2H_2O$	0.19661
$MgCl_2 \cdot 6H_2O$	0.08364
$BaCl_2 \cdot 2H_2O$	0.00533
$SrCl_2 \cdot 6H_2O$	0.00486
$NaHCO_3$	2.50311

Two synthetic high molecular weight hydrolyzed polyacrylamides (HPAM) polymers and one bio-polymer are used in this work. Polymer solutions are prepared at three concentrations 500 ppm, 1000 ppm and 1500 ppm. The preparation procedure used is the one adopted by Hincapie and Ganzer, [20]. A detailed description of polymers is provided in **Table 2**. Diluted polymer solutions are filtered using a membrane filter with a size of 1.2 µm (pre-sheared solutions) and 5 µm (non-sheared solutions). Purpose of pre-shearing of polymer solution is well documented by Hincapie, [15], Hincapie and Ganzer, [20]. It attempts to evaluate polymer stability, injectivity and viscoelastic properties. Shearing is performed by injecting polymer solutions through shearing device with the principle of flow through small nozzles, proposed by Hincapie and Ganzer, [20]. The shearing is done by applying 30 bar pressure with the purpose of degrading the macromolecules of the polymer without affecting polymer's yield viscosity. This approach is expected will reduce potential injectivity problems as pointed by Hincapie and Ganzer, [20].

2.2. Porous Media

Bentheimer core plugs are used in this work, with an average length and diameter of 60 mm and 30 mm, respectively. Core plugs were dried by placing them in an oven at 60˚C for at least 5 days. Porosity was measured using a Micromeritics 1340 pycnometer and permeability using a Gas Permeameter. Brine was injected at five different injection rates (0.5. 1.0, 2.0. 5.0, and 10.0 ml/min) to measure brine permeability. **Table 3** provides a summary of the core plugs.

Table 2. Characteristics of polymers used for the discussed experiments.

Polymer	MW (Million Daltons)
Flopaam 6035S	24 - 28
Hengfloc 63026	26
Actigum CS 6	8

Table 3. Porous media characteristics used for core flooding/sand-pack.

Nr.	Name	Type	Length (cm)	Diameter (cm)	Dry wt. (g)	Poro. (%)	Perm. (g) (mD)
1	M_1	Core	6.02	2.918	80.43	24.64	2190
2	M_4	Core	6.00	2.93	80.94	24.74	2410
3	M_5	Core	5.75	2.92	76.96	24.64	2150
4	M_6	Core	5.99	2.93	81.02	24.65	2009
5	M_7	Core	6.01	2.93	80.84	24.94	2230
6	M_8	Core	6.00	3.00	86.151	23.38	1980
7	M_{10}	Core	6.01	2,95	82.83	28.05	2125
8	SP_{09}	Sank-Pack	6.28	3.32	-	45.58	-

Quartz sand with grain size range of 63 - 80 μm screened was selected for sand-pack experiments. Average length and diameter of sand packs was same as those of core plugs. Porosity of sand-packs is measured through mass balance and volume balance method while permeability calculation is done using Darcy's law by brine injection. Apart from that, stainless steel capillary tube (CT) of 0.5 mm ID and 3 m length is used to investigate impact of no converging-diverging geometry on polymer solution.

3. Experimental Procedure

Figure 2 presents a descriptive and detailed sequence of the key experimental procedures adopted throughout this study.

3.1. Single-Phase Core Flooding

Figure 3 provides a schematic representation of the core-flood setup [15]. It consists of a two-syringe injection pump connected in a multi-flow arrangement (infusion/withdrawal) and controlled by irreversible check valves. The core plug is placed in a core holder that receives confining pressure, applied using a positive displacement hand pump. A rubber sleeve is used to secure the core plug inside the core holder. We used a pressure transmitter to gather pressure data. The confining pressure was kept constant at 30bar to guarantee radial flow. Once calibrated, the pressure transducer measured the pressure difference between the holder's inlet and exit ports, with the data recorded on a computer.

3.2. Single-Phase Sand Packs Injection

Single-phase sand pack experiments were performed with an essentially similar setup as the one shown in Figure 3. The experiment started with the preparation of the sand; placing it into the cell and previously weighing the dry mass of

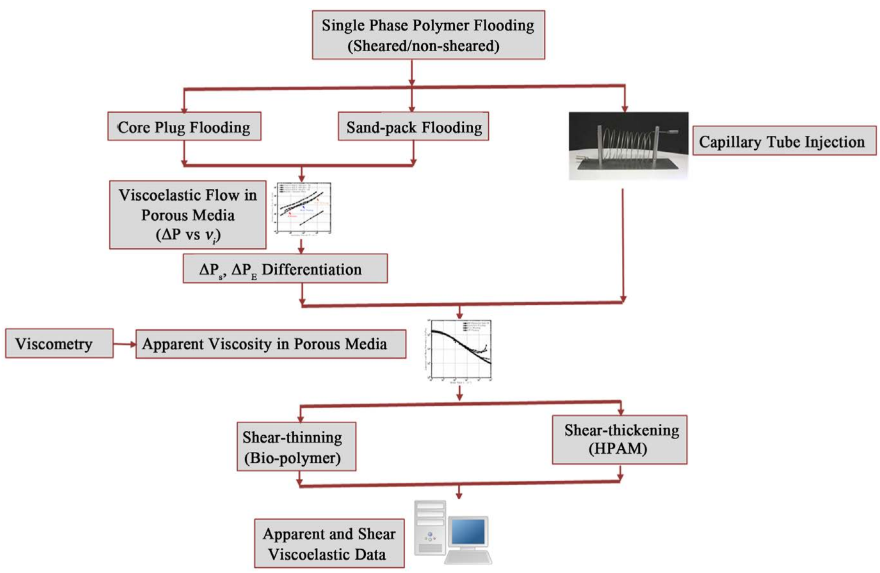


Figure 2. Descriptive flow chart of key experimental procedures adopted in this study.

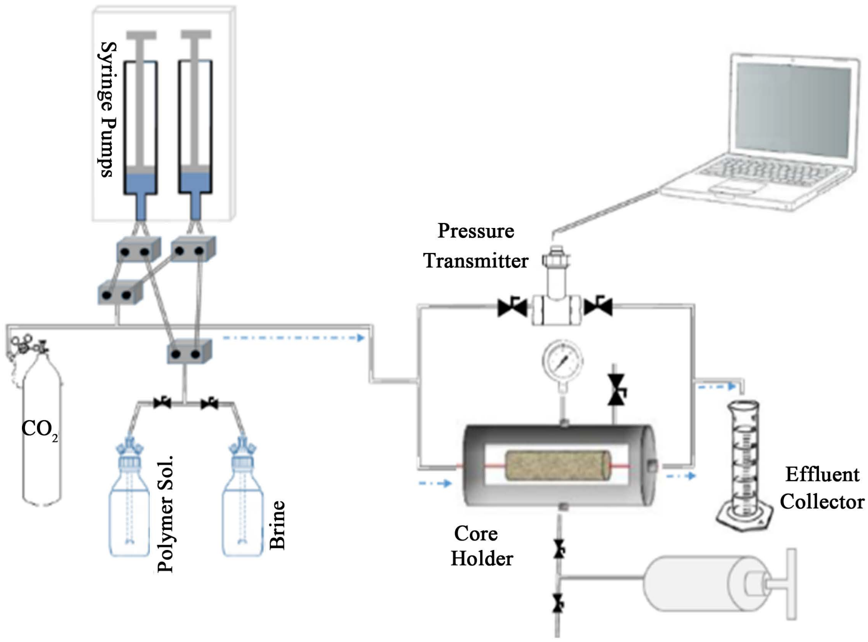


Figure 3. Sketch of core flood experimental setup. It is connected via PTFE Teflon tubing and stainless steel pipes to the syringe pump and a differential pressure gauge.

the sand pack. The sand pack was subsequently saturated with CO2 prior to brine injection. This was to remove air bubbles and thus avoid air bubbles effect. After sufficient brine had been injected into the sand pack, permeability was determined. The procedures undertaken to perform the sand pack experiments were similar to those described for core plug experiments.

3.3. Single-Phase Capillary Tube (CT) Injection

A CT (capillary tube) with an internal diameter of 0.5 mm and length 2.5 m was shaped into a helical structure as shown in **Figure 4**. Results from this approach are compared with results of core flooding and sand-pack injection. Experimental components e.g. Pressure measurement device and injection pump are the same as discussed in previous sections.

4. Results and Discussions

4.1. Measurement of Pressure Drop across the Sand Packs and Cores

Viscoelastic phenomenon of polymer can be observed by drawing a similar scheme to that proposed by Heemskerk *et al.* [14], Hincapie, R., [15], Tahir *et al.*, [21]; where the measured pressure drop during polymer flooding experiments is plotted against interstitial velocity.

Heemskerk's work described shear thinning behavior for a slope below 45˚, shear thickening for a slope greater than 45˚, and a Newtonian response for a slope of precisely 45˚. The results presented here are in exceptionally good agreement with those reported by Heemskerk *et al.* [14], Hincapie, [15], Tahir

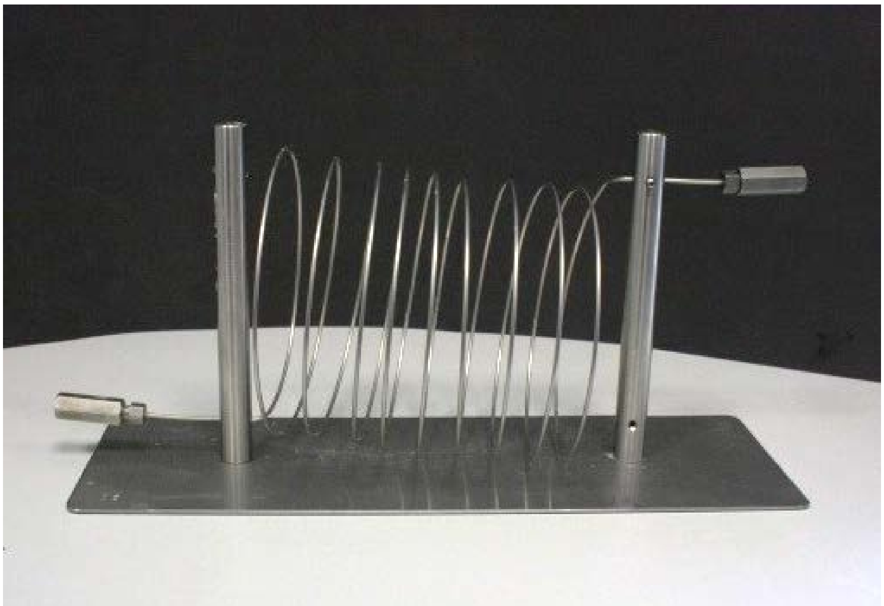


Figure 4. Stainless steel capillary tube (CT) setup. Designedto compare apparent viscosity in core flood and sand-pack flood (impact of converging-diverging geometry).

et al., [21]. Figure 5 illustrates the following clearly observed behaviors of HPAM polymer solutions (pre-sheared and non-sheared): a characteristic slope for a Newtonian response at 45˚, shear thinning below 45˚, and shear thickening behavior above 45˚.

4.2. Pressure Drop Differentiation by Shear and Elongation

A typical plot to represent the pressure response is one where pressure response is related to injection flow rates or interstitial velocity [15] [21]. The overall approach taken in this work is reported in Figure 6(a) for the Bentheimer core plug and in Figure 6(b) for a sand pack experiment.

The plot considers the total pressure (ΔP_T) obtained during the core flooding measurement and the pressures associated with shear (ΔP_{Sh}), determined using Darcy's law. These results enable determination of the pressure drop assumed to be by elongation (ΔP_{Elo}). It would appear from Figure 6 that the calculated pressure drop only matched the experimental data at low interstitial velocity.

$$\Delta P_T = \Delta P_S + \Delta P_E$$

where,

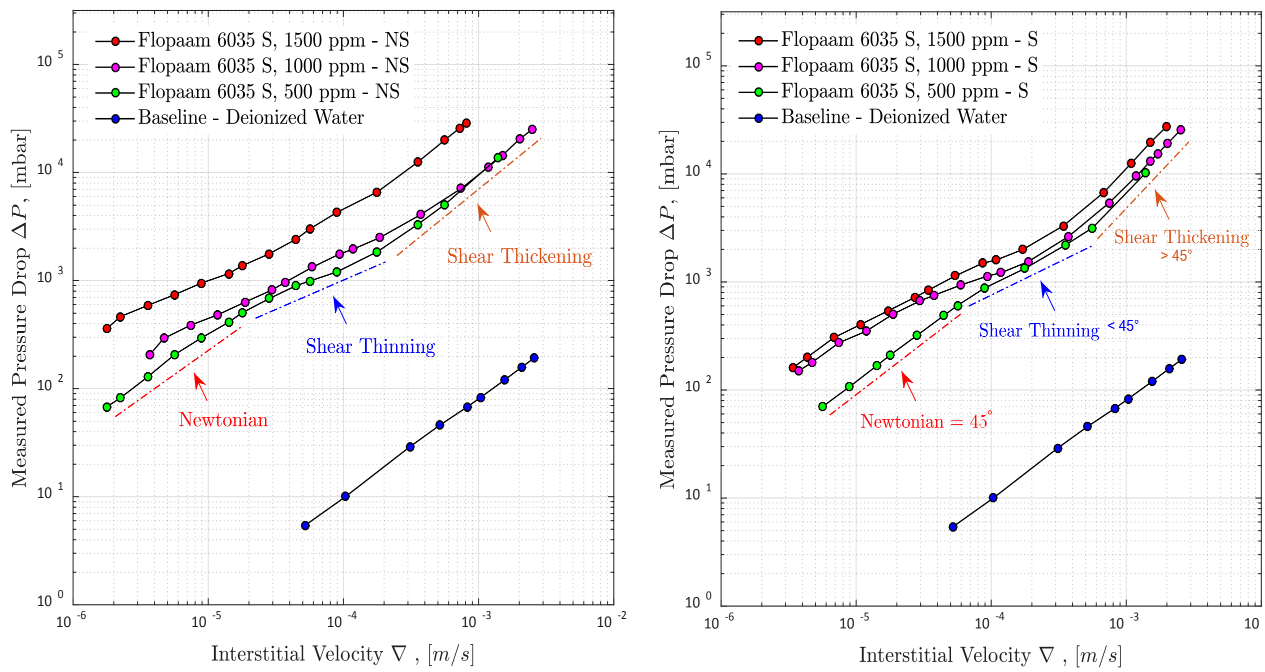
ΔP_T = Total pressure obtained during the core flooding

ΔP_S = Determined using Darcy equation and Carreau-Yasuda flow curve fitted to rheometer data

ΔP_E = Pressure drop by elongation = $\Delta P_T - \Delta P_S$.

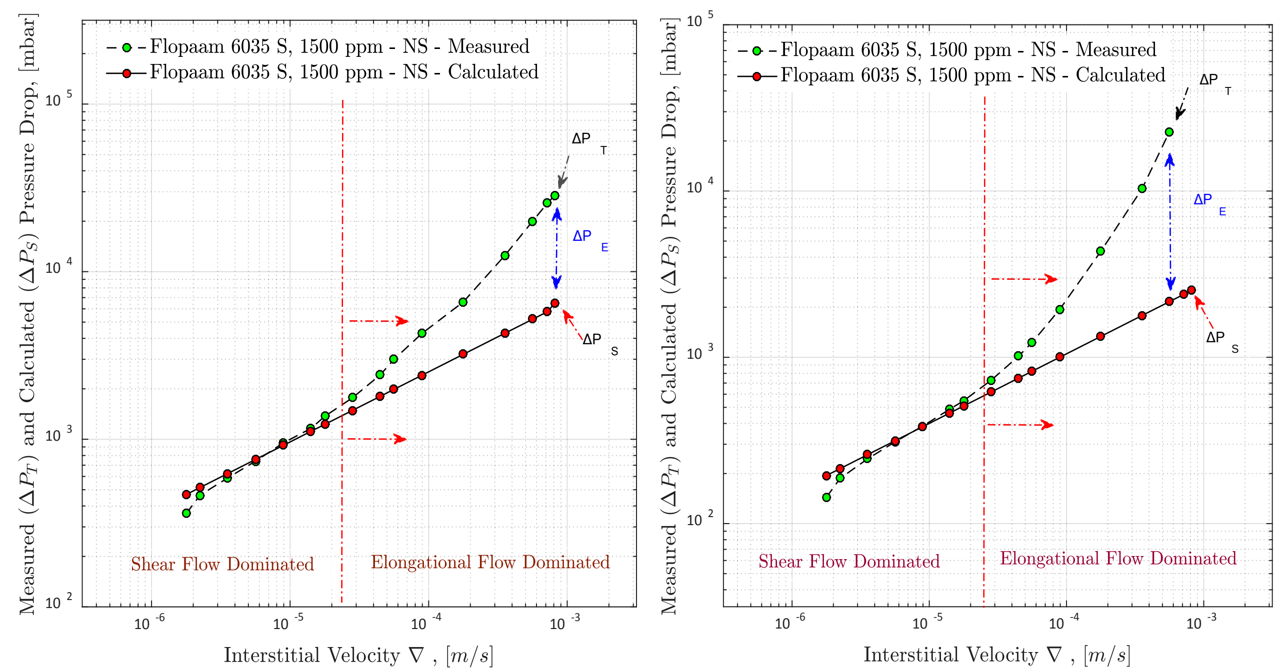
4.3. Evaluation of Apparent Viscosity over Shear Rates for Sand Packs and Cores

Typical plots to compare the matching between bulk viscosity and apparent



(a) (b)

Figure 5. Measured pressure drop as a function of interstitial velocity for an HPAM solution through a Bentheimer core plug. The data plotted is for the HPAM Flopaam 6035 S, non-sheared (a) and pre-sheared (b) at different concentrations in a 4 g/l TDS brine solvent. Pressure data plotted is the one recorded during the experiment by flooding polymer solutions for different injection rates.



(a) (b)

Figure 6. Measured and calculated pressure drop as a function of interstitial velocity for a HPAM solution through a Bentheimer Core (a) and Sand-pack (b). The data plotted is for the HPAM Flopaam 6035 S, non-sheared at 1500 ppm in a 4 g/l TDS brine solvent. Measured data plotted is the one recorded during the experiment by flooding polymer solutions for different injection rates. Calculated pressure is the one obtained by Darcy equation and the Carreau-Yasuda flow curve fitted to rheometer data.

viscosity are shown in **Figure 7**. It is a common practice to present the data in such a way because it enables demonstrating the differences observed during the core flooding to data obtained in the rheometer. **Figure 7(a)** presents a comparison of the different approaches in the case of a hydrolyzed polyacrylamide (HPAM) solution. Approach 1 is based upon equation used for shear rate calculation proposed by Cannella *et al.*, [7], the approach 2 is taken from the equation proposed by Christopher and Middleman, [17], the approach 3 is taken from Lee, [22] and the approach 4 is evaluated from the equation presented by Sheng, [23]. A summary of the shear rate correction coefficients is given in **Table 4**. Moreover, **Figure 7(b)** depicts the case for a biopolymer. Note that it is important to point out the differences of both plots. There was a tendency for the viscosity of the HPAM to increase at a certain apparent shear rate. This tendency

Table 4. Shear rate coefficients for solutions.

Polymer	Con.	Brine	Por. Media	Conc.	Shear Rate Coefficient			
	NS/S	g/L	Core/SP	ppm	App. 1	App. 2	App. 3	App. 4
Hengfloc 63026	NS	4	Core	1500	0.55	0.32	0.45	0.20
Actigum CS 6	NS	4	Core	1500	-	-	-	-
Hengfloc 63026	NS	4	Sand-Pack	1500	115	80	85	0.30
Hengfloc 63026	S	4	Core	1500	0.40	0.30	0.35	0.10
Hengfloc 63026	NS	4	Core	1000	0.12	0.12	0.12	0.10
Flopamm 6035 S	NS	4	Core	1000	0.15	0.10	0.10	0.06

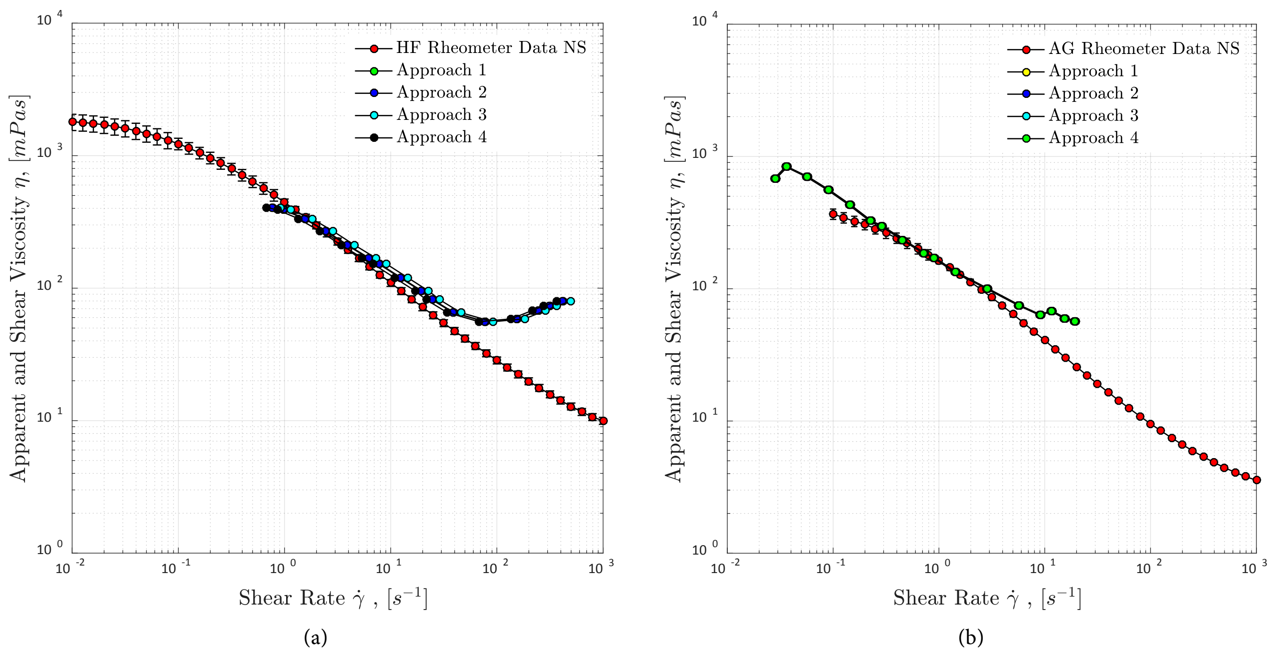


Figure 7. Apparent flow curves obtained by relating the bulk viscosity to core flooding. The data shown belong to a Hengfloc 63026 1500 ppm non-sheared in a 4 g/l TDS brine solvent (a) and a biopolymer Actigum CS6 1500 ppm non-sheared in a 4 g/l TDS brine solvent (b).

was not observed for the biopolymer. It is evident that these results demonstrate flow thickening or flow thinning in the porous media. This is pointed as a characteristic of flow in porous materials that is not observed in rheological measurements at similar rates. Similar observations have been presented previously by Cannella *et al.*, [7], Hejri *et al.*, [24], Teeuw and Hesselink, [25]. The results presented here are in good agreement with those reported in the literature.

Shear rates and apparent viscosity calculations using two different type of porous media (Bentheimer core and Quartz sand-pack) and CT are shown in **Figure 8** for Hengfloc 63026 polymer solution. From **Figure 8** it can be observed that the apparent viscosity and shear rates are calculated using the approach 1. As can be seen the core flooding and sand-pack data depicted an increased apparent viscosity due to the increment in pressure. This phenomenon has been previously observed as an onset. This is assumed to be related to stronger viscoelastic properties at higher shear rates. Unlike core flooding and sand packs, for the case of the CT experiments the only shear thinning behavior is observed. This is due to: 1) non-existence of pore size distribution (contractions-expansions) in CT and 2) it is indeed a pipe flow (expected behavior). One

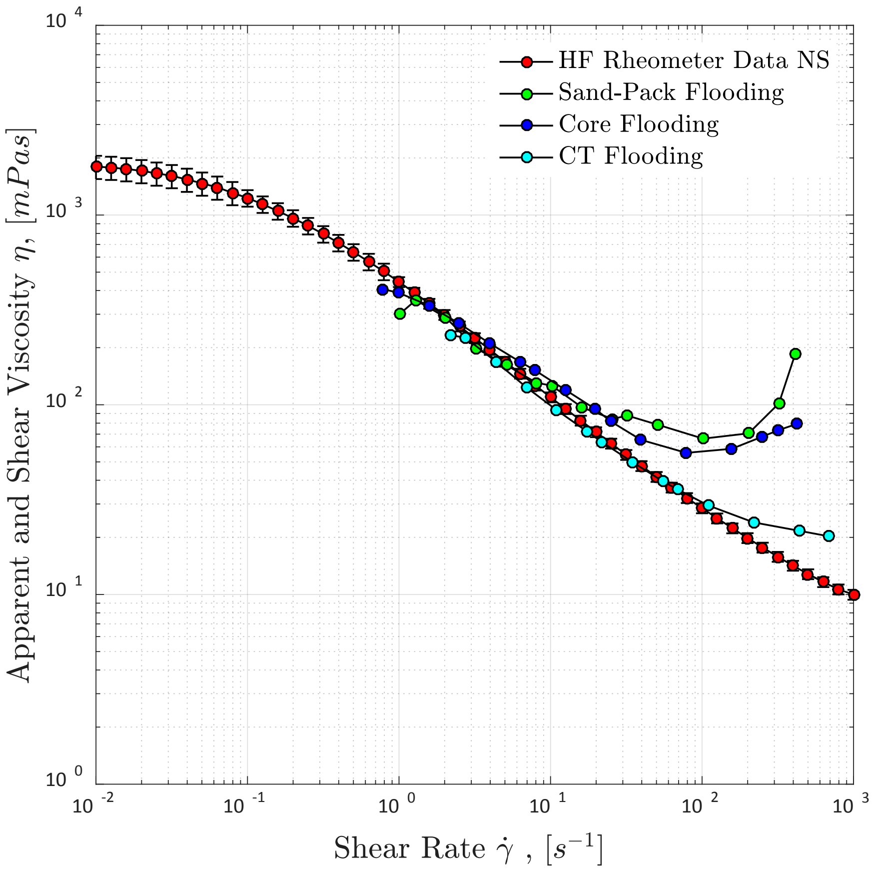


Figure 8. Apparent flow curves obtained by relating the bulk viscosity to core flooding, sand-pack and capillary tube injection. The data shown belongs to a Hengfloc 63026 1500 ppm non-sheared in a 4 g/l TDS brine solvent. Approach 1 is used for apparent shear rate calculation.

can argue that the apparent viscosity in sand-pack experiments is higher compared to the core flooding. This is explained by the variation in pore size distribution due to the sand grain size, as well as the differences in permeability and porosity, due to the low compaction.

Comparing shearing conditions of solutions given in **Figure 9(a)**, sheared polymer showed lower bulk and apparent viscosity as related to non-sheared solutions over low shear rate values (1 s^{-1}). This was expected behavior as mechanical shearing break-downs the molecular chains of polymer to avoid injectivity problems. But at higher shear rates (100 s^{-1}), rheometer bulk viscosity for shear and non-sheared solution was almost same. At these higher shear rates, apparent viscosity for sheared solution was higher than non-sheared solution. This is because sheared polymers have less viscous forces as compare to non-sheared polymers. Thus less viscous forces will result more ease in flow and will result to dominance of turbulent pressure drop. This excessive pressure drop will contribute excessive apparent viscosity. But contribution of turbulence pressure drop at high injection rates need to be calculated [21]. Also in **Figure 9(b)** is the comparison of Flopaam 6035 S and Hengfloc 63026 1000 ppm non-sheared in a 4 g/l TDS brine solvent. Flopaam 6035S showed higher bulk and apparent viscosity as compare to Hengfloc 63026 solution. Reason could be difference in molecular structure and molecular weight of polymers (**Table 2**). Due to higher bulk and apparent viscosity, Flopaam 6035 S also showed injectivity issues as compare to Hengfloc 63026 in sand-packs.

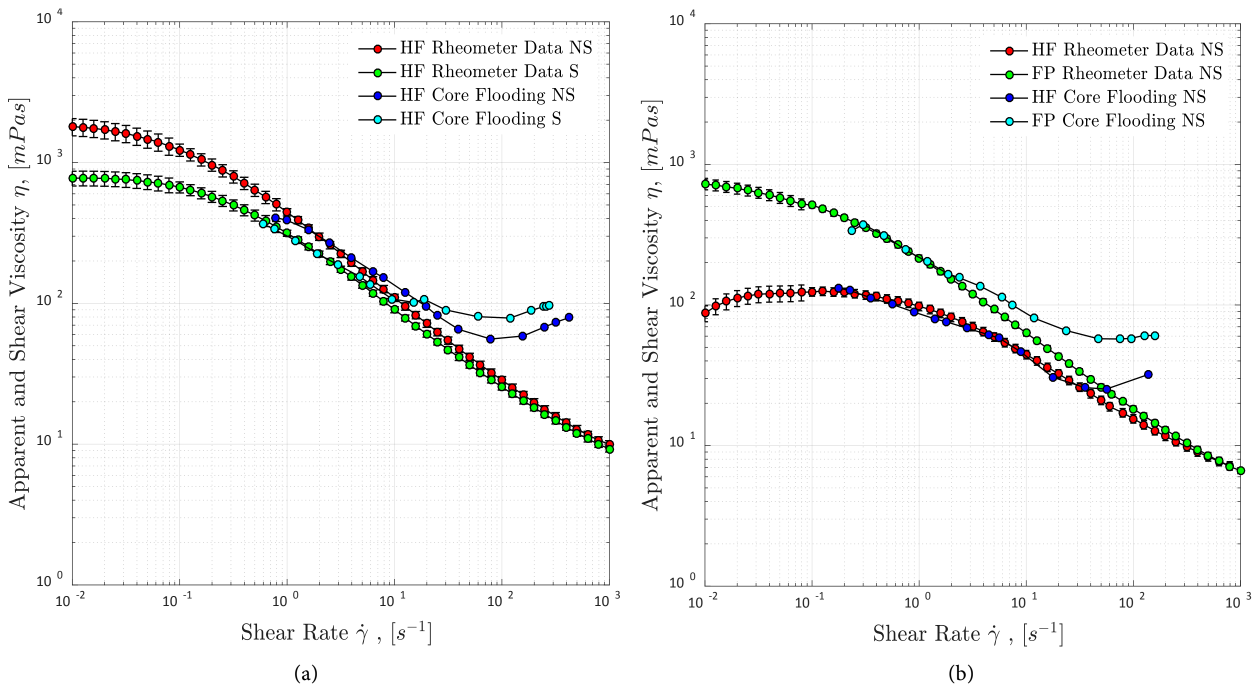
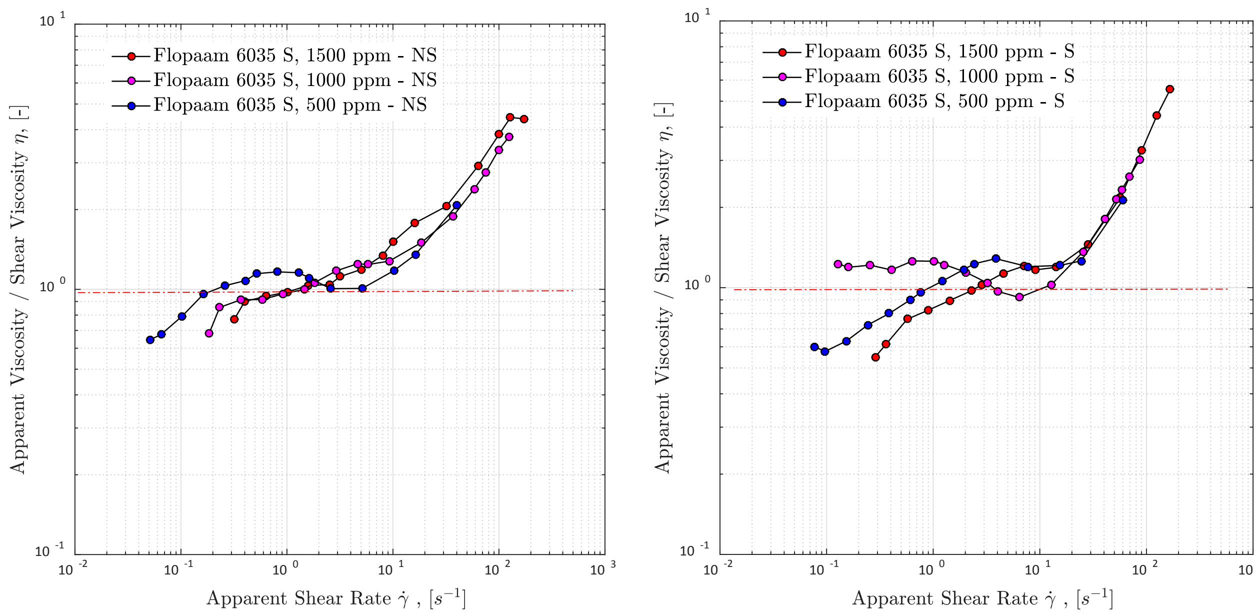


Figure 9. Apparent flow curves obtained by relating the bulk viscosity to core flooding. The data shown on (a) belong to a Hengfloc 63026 1500 ppm non-sheared/sheared in a 4 g/l TDS brine solvent. The data shown on (b) belong to a Hengfloc 63026 1000 ppm non-sheared and Flopaam 6035 S 1000 ppm non-sheared in a 4 g/l TDS brine solvent. Approach 1 is used for apparent shear rate calculation.

4.4. Apparent Viscosity Related to Steady Shear Viscosity

The flow behaviour of an HPAM in a rheometer experiment compared to that in a core flooding experiment is commonly expressed as shown in Figure 10. Since the purpose in this work was to describe that onset or shear thickening, a different approach was chosen. Howe *et al*., [26] proposed a plotting approach from observations in microchannel that seem to be useful, as expressing the behaviour observed in core plugs. The suggested evaluation is based on plotting the normalized data obtained by taking the apparent viscosity (measured during core experiments) divided by bulk viscosity (rheometer) against the apparent shear rate. As reported by Howe *et al*., [26], this manner of plotting is equivalent to plotting the measured pressure during core experiments divided by behaviour expected according to Darcy's equation.

The results obtained for Flopaam 6035 S non-sheared and at different concentrations, are depicted in Figure 10(a). It is evident from the plot that at a certain shear rate the onset of elasticity occurs. This is consistent with results obtained by Howe *et al*., [26] and clearly indicates non-dependence of this onset on polymer concentration. This is contrary to the generally accepted assumption often made by the authors in petroleum related literature. For instance, it is assumed that elasticity in porous media depends strongly on the linear viscoelasticity (the one observed in small amplitude oscillatory SAOS measurements). As reported by Hincapie *et al*., [27], SAOS can provide an insight only on whether a polymer might be elastic or inelastic, but it fails to predict the behaviour under flow. A similar trend was observed for pre-sheared solutions Figure 10(b).



(a) (b)

Figure 10. Ratio between apparent viscosities measured in Bentheimer core plugs and Bulk viscosity by fitting the Carreau-Yasuda model plotted against the apparent shear rate corrected by rheometer data. The data plotted is for the HPAM Flopaam 6035 S, non-sheared (a) and pre-sheared (b) in a 4 g/l TDS brine solvent.

Comparing Figure 10(a) and Figure 10(b) shows that an early onset seemed to occur for the non-sheared solutions. Quantitatively the ratio of apparent viscosity and bulk viscosity above 50% was found to be around 30 s^{-1}, where the onset started for the non-sheared solutions and around 70 s^{-1} for the pre-sheared solutions. This was determined by observing the deviation of the ratio from the unity.

Additional support can be given to the results obtained in this work by considering the Weissenberg number. The Weissenberg number is described as a measure of the degree of nonlinearity or that degree to which normal stresses manifest during the flow [28]. For simplicity it can be considered as the product of the relaxation time (of the fluid) and the characteristic shear rate of the flow. In other words relaxation times obtained in Small Amplitude Oscillatory Shear (SAOS) multiplied by the apparent shear rate determined for each measurement. It can be observed in Figure 11 that the onset corresponded to the elastic properties of the polymer solutions. It could be inferred then, as reported by Hincapie, [15], Howe *et al.*, [26] that flow instabilities are related to elastic turbulence.

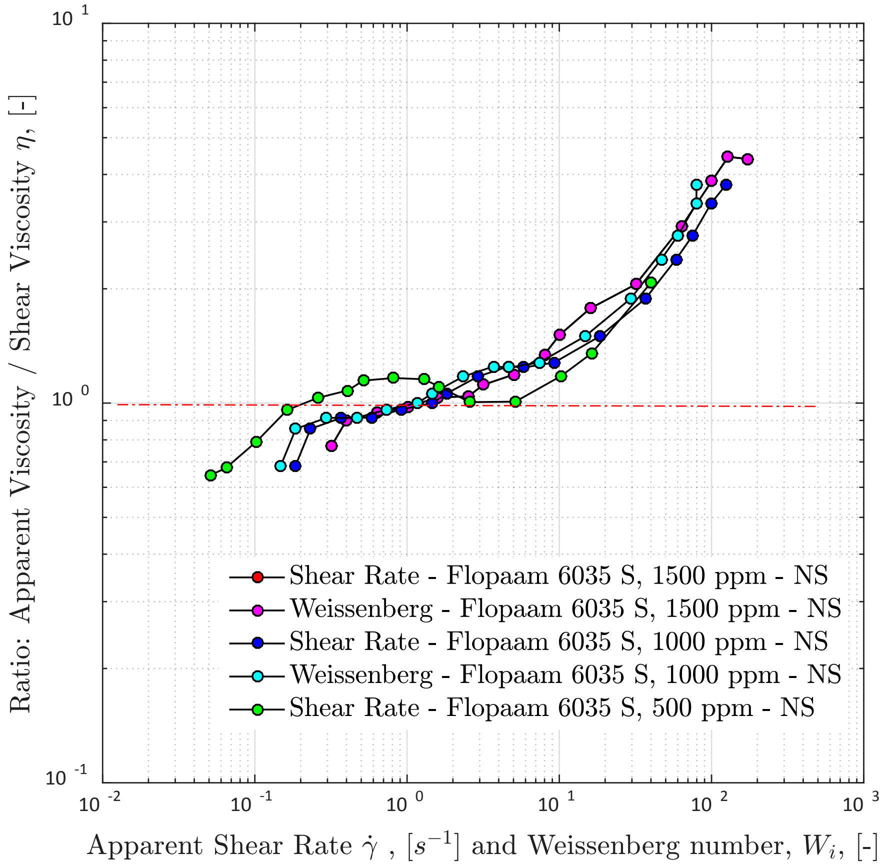


Figure 11. Ratio between apparent viscosity measured in Bentheimer core plugs and bulk viscosity by fitting the Carreau-Yasuda model plotted against the apparent viscosity corrected by rheometer data as well as Weissenberg number. The data plotted is for the HPAM Flopaam 6035 S, non-sheared at different concentrations in a 4 g/l TDS brine solvent.

5. Summary and Conclusion

A detailed investigation of polymer viscoelasticity is performed and summarized using various approaches suggested by researchers from rheometer to its response in porous media. When comparing data obtained for core and sand pack experiments, there was a tendency for the viscosity of HPAM to increase at a certain apparent shear rate. This was not observed for the biopolymers. These results demonstrate flow thickening in the porous media. Further these observations were noted as a characteristic of flow in porous materials that was not observed in rheological measurements and CT injection at similar rates. Further evaluations on the shear thickening behaviour were achieved by plotting the normalized data against the apparent shear rate. The normalized data was obtained by dividing the apparent viscosity (measured during core experiments) by bulk viscosity (rheometer). It is evident from the plot that at a certain shear rate, the onset of elasticity is clearly seen. It is clear that this onset is independent of polymer concentration. Additional support to the elastic onset evaluation obtained in this work was given by considering the Weissenberg number. The following were clearly observed in polymer flooding in porous media: a characteristic slope for Newtonian behaviour equal to 45˚, shear thinning behaviour below to 45˚ and shear thickening behaviour above 45˚. As expected, a concentration dependence related to the pressure was observed. Based on this pressure differentiation, it was evident that the pressure drop occurring in the sand pack and core experiments were not only due to shear deformation, but also due to elongational deformation. Therefore to estimate the elongational pressure drop additional parameters need to be integrated.

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