

Rheology-based method for calculating polymer inaccessible pore volume in core flooding experiments

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Abstract. Polymer flooding is an enhanced oil recovery (EOR) method that reduces the mobility ratio between the displaced oil and the displacing injected water. The flow of polymer solutions through porous media is subject to some process-specific phenomena, such as the inaccessible pore volume (IAPV). Due to IAPV, polymer molecules move faster through the porous medium than smaller ones. Thus the IAPV value needs to be accounted for in experiments and field projects. Recent reports found that polymer in-situ rheology correlates with the IAPV. The objective of this paper is to develop a method for estimating IAPV based on the in-situ rheology of polymers. The methodology proposed here can be used in both single- and two-phase experiments. The technique requires measurement of polymer resistance factor (RF) and residual resistance factor (RRF) at steady state conditions. Core permeability, porosity, and residual oil saturation, as well as water and polymer bulk viscosities, also need to be taken into account. Correlations for polymer in-situ viscosity and shear rate are solved simultaneously, to yield an estimative for the IAPV. Aiming at to prove the method, we report 16 core-flooding experiments, eight single- and eight two-phase experiments. We used a flexible polymer and sandstone cores. All the tests were run using similar rock samples. In the single-phase experiments, we compare the alternative method with the classic tracer method to estimate IAPV. The results show an average relative difference of 11.5% between the methods. The two-phase results display, on average, an 18% relative difference to the IAPV measured in the single-phase experiments. The difference between single- and two-phase results can be an effect of the higher shear rates experienced in the two-phase floodings since, in these cases, the aqueous phase shear rate is also dependent on the phase saturation. Additionally, temperature, core length, pore pressure, and iron presence on the core did not show any influence on the IAPV for our two-phase experiments. The method proposed in this paper is limited by the accuracy of the pressure drop measurements across the core. For flexible polymers, the method is valid only for low and mid shear rates, but, according to literature, for rigid polymers the method should be accurate for a broad range of shear rates. The method proposed here allows the measurement of polymer IAPV on two- and single- phase core-flooding experiments when a tracer is not used.

1 Introduction

Polymer flooding is an enhanced oil recovery method (EOR) which consists in the addition of water-soluble polymers in the injection water. This polymer addition results in an increase of the injected fluid viscosity, and thus, the mobility ratio between displacing (water) and displaced (oil) fluids is reduced [1]. Mobility ratio reduction improves the volumetric sweep efficiency by reducing viscous fingering [2] and channeling effects [1]. Thus, polymer flooding can be advantageous for heavy oil recovery or heterogeneous reservoirs [1] and was successfully applied in sandstone and carbonate reservoirs [3]. Polymer flow in porous media is subject to specific phenomena, such as non-Newtonian viscosity and inaccessible pore volume (IAPV).

Polymer IAPV is a phenomenon that results in the transport of polymer molecules through a smaller pore volume than the one available for small molecules (i.e., salts) [1]. That results in faster transport of polymer species through the porous medium than those small molecules [4].

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There are two explanations for the IAPV: 1. IAPV is an effect of blocked pores and pores that are too small compared to the polymer molecular size [4], a concept similar to that of gel permeation chromatography [5]. 2. IAPV is a consequence of the depleted layer, a thin layer of polymer-free liquid resulted from entropic (or steric) exclusion of large molecules from the pore walls [6, 7]. Fig. 1 represents the two interpretations for the polymer IAPV.

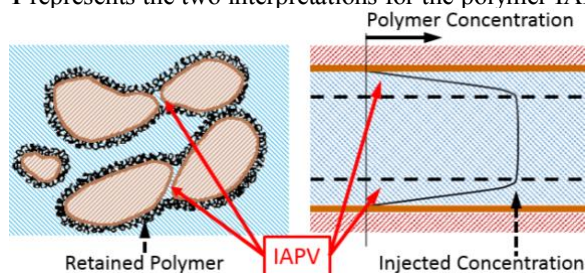


Fig. 1. The two interpretations for the polymer IAPV. Left: illustration of a porous medium with blocked pores; Right: polymer concentration profile illustrating the depleted layer near pore walls (adapted from [6]).

Polymeric solutions for EOR applications are shear-thinning fluids, and their bulk rheology can be estimated through rheometers. However, polymer apparent viscosity when flowing through a porous medium (i.e., *in-situ* viscosity) differs from the bulk viscosity [8, 9]. There are four distinct *in-situ* viscosity regions for flexible polymers (e.g., HPAM) [8]: 1. Newtonian plateau at low shear rates; 2. shear-thinning region at medium shear rates; 3. shear-thickening region at high shear rates due to viscoelastic effects; 4. another shear-thinning region at very high shear rates due to mechanical degradation. For polymers with rigid structures (e.g., xanthan in its ordered state), the region 3 does not exist, since these polymers do not present viscoelastic behavior. Fig. 2 illustrates the bulk and *in-situ* viscosities for flexible polymers. The viscosity behavior of regions 1 and 2 are similar to bulk viscosity, however *in-situ* viscosity is lower than bulk viscosity due to an apparent slip effect caused by the depleted layer [9], and thus, linked to the IAPV.

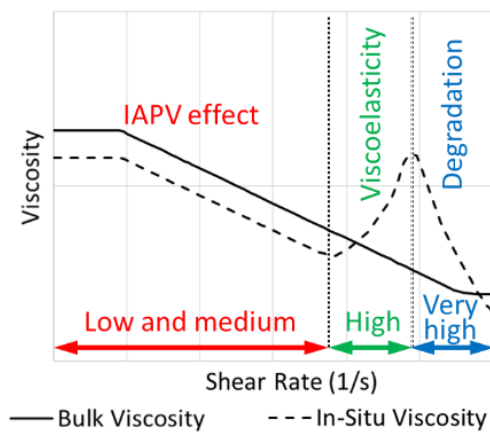


Fig. 2. Synthetic bulk (line) and *in-situ* (dash) viscosities for flexible polymer. Effects that change the *in-situ* viscosity: IAPV for low and medium shear rates (red), viscoelasticity for high shear rates (green), and mechanical degradation for very high shear rates (blue) (based on [8]).

The conventional method for estimating polymer IAPV is based on the core flooding in the presence of a polymer and an inert tracer. Effluent analysis to determine the polymer and tracer breakthrough instants are required to estimate the IAPV. Determination of polymer concentration may require complex methods and/or equipment, and often the presence of oil is a contaminant to those measurements [3, 10, 11].

The objective of this paper is to develop a method for estimating IAPV based on the *in-situ* rheology of polymers. The method should require pressure drop measurements in core flooding and rheology experiments and could be used in both single- and two-phase experiments.

2 Materials and methods

Rocks. All the experiments were carried out in sandstone cores. The cores were obtained from an outcrop of the Botucatu formation (Paraná basin, PR, Brazil), which is similar to Berea sandstone and adequate for core-flooding

experiments [12]. A total of ten samples were used in the experiments. Table 1 and

Table 2 compile the sample characteristics. Before the core-flooding experiments, all the samples were cleaned with methanol and toluene by soxhlet extraction and then dried overnight in a 100°C oven. The Botucatu samples have iron oxide in their composition [13], and iron minerals are known to affect polymer adsorption [11], and degradation [14]. Therefore, some samples were chemically treated with hydrochloric acid to remove the iron [15].

Fluids. Three fluids were used in our experiments: polymeric solution, brine, and oil. The aqueous fluids had high salinity and hardness.

Table 3 summarizes the composition of both the polymer and brines used. The solvent for the water-phase fluids was deionized water.

We used the polymer Flopaam 5115SH, a high molecular weight (15×10^6) terpolymer consisting of polyacrylamide, hydrolyzed polyacrylamide, and AMPS. This polymer is indicated for applications under high temperature and high salinity conditions [16]. The polymeric solutions were prepared following the procedures of API RP 63 [10]. The bulk rheology characterization of this polymeric solution was presented in a previous work [17].

In the single-phase (SP) experiments, two brines were used, one of 10.5% TDS, and another with 5.75% TDS. These compositions were used so that the difference in salt concentration would act as a tracer, and the IAPV could be determined by the conventional method. For the two-phase (TP) experiments, only one brine composition was used.

In the experiment TP-5 (sample 14C7A), we used a mineral oil of 24cP viscosity. For every other two-phase experiment, we used a field oil with viscosity adjusted to be 180cP at the experimental conditions (regardless of temperature). The viscosity of the field oil was adjusted by mixing kerosene until the desired viscosity was achieved [15].

2.1 Core flooding

The SP and TP core flooding were performed in similar workbenches, as illustrated in Figure 3. Following Figure 3, an ISCO syringe dual pump injected water into an oil container. The oil was then used to displace either brine or polymer or to be injected into the core (oil injection only for TP). The 3/2-way valves selected which fluid to be injected into the core, which was confined in a core-holder. The confining pressure was 3000psi for the long samples (>200mm) and 900psi for the short ones (~60mm). A series of sensors were used to measure desired properties, as summarized in Table 4. A back pressure regulator and a heating apparatus were used in some experiments, as identified by Table 1 and

Table 2.

The single-phase experiments consisted of a polymer injection followed by a brine one. These experiments were conducted

in porous media that had been previously flooded with polymer to satisfy adsorption and then were re-saturated with brine. A virgin porous medium was not used because the

classic method to measure IAPV leads to wrong results when adsorption is acting.

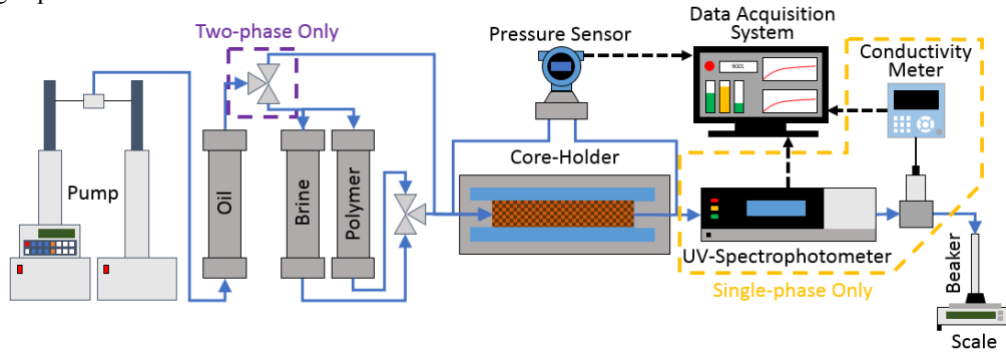


Fig. 3. Schematic of the experimental apparatus used in the core-flooding experiments.

Table 1. Summary of the conditions and results for the two-phase core-flooding experiments.

Experiment ¹	TP-1	TP-2	TP-3	TP-4	TP-5	TP-6	TP-7	TP-8
Rock ID	8A2A	14C8A	14C4A	14C6A	14C7A	14C3A	14C9A	14C3B
Iron treatment	No	Yes	No	No	Yes	No	No	No
Back pressure (psi)	none	none	400	400	400	none	none	none
Temperature (°C)	23	23	23	23	23	60	60	55
Length (mm)	236	62.7	62.2	63.1	60.6	61.0	59.0	275
Diameter (mm)	36.6	37.5	37.6	37.7	37.6	37.7	37.7	37.7
Gas porosity	0.29	0.33	0.34	0.34	0.33	0.31	0.32	0.27
Water absolute permeability (mD) ²	8247	7436	5528	6829	9736	4104	4127	4267
Water effective permeability (mD) ³	43	101	88	28	20	79	113	62
Residual oil saturation	0.36	0.42	0.47	0.31	0.27	0.25	0.41	0.41
Flow rate (cm ³ /min)	0.38	0.71	0.7	0.7	0.7	0.72	0.71	0.41
<i>In-situ</i> shear rate (s ⁻¹)	482	511	485	1204	1303	830	489	437
Polymer bulk viscosity (cP) ⁴	4.43	4.08	4.78	3.89	3.98	3.50	3.88	3.88
Polymer <i>in-situ</i> viscosity (cP)	3.14	2.87	3.36	2.60	3.15	1.86	2.27	2.01
Brine viscosity (cP)	1.130	1.218	1.287	1.296	1.287	0.610	0.632	0.620
IAPV: rheology-based method	0.239	0.298	0.264	0.429	0.192	0.394	0.276	0.382

1. TP indicates two-phase core flooding; 2. Absolute permeability measured before the sample had contact with any oil or polymer; 3. Effective permeability measured after the RRF effect and at residual oil saturation; 4. Bulk viscosity measured on the rheometer at the same shear rate as the one measured in the core flooding.

Table 2. Summary of the conditions and results for the single-phase core-flooding experiments.

Experiment ¹	SP-1	SP-2	SP-3	SP-4	SP-5	SP-6	SP-7	SP-8
Rock ID	14C18A1				14C18A2			
Iron treatment	No				No			
Back pressure (psi)	none				none			
Temperature (°C)	23				23			
Length (mm)	62				64.3			
Diameter (mm)	37.8				37.7			
Gas porosity	0.26				0.31			
Water absolute permeability (mD) ²	5135				5360			
Water effective permeability (mD) ³	2342	2576	1712	1906	1403	1456	1636	1849
Flow rate (cm ³ /min)	0.4	0.6	0.8	1	0.25	0.4	0.6	0.8
<i>In-situ</i> shear rate (s ⁻¹)	47	57	102	114	31	50	68	83
Polymer bulk viscosity (cP) ⁴	6.68	6.47	5.91	5.80	7.2	7.24	7.40	7.67
Polymer <i>in-situ</i> viscosity (cP)	3.42	4.30	3.48	3.81	4.21	4.17	4.47	5.02
Brine viscosity (cP)	1.103	1.103	1.103	1.103	1.103	1.103	1.103	1.103
IAPV: rheology-based method	0.411	0.197	0.315	0.228	0.262	0.273	0.233	0.177
IAPV: tracer-based method	0.297	0.239	0.233	0.255	0.173	0.246	0.173	0.263

1. SP indicates single-phase core flooding; 2. Absolute permeability measured before the sample had contact with any polymer; 3. Effective permeability measured after the RRF effect. 4. Bulk viscosity measured on the rheometer at the same shear rate as the one measured in the core flooding.

Table 3. Composition of brine and polymeric solution for the single- and two-phase experiments.

Fluid	Experiment	5115SH ¹ ppm ²	NaCl ppm ²	KCl ppm ²	Na ₂ SO ₄ ppm ²	CaCl ₂ ·2H ₂ O ppm ²	MgCl ₂ ·6H ₂ O ppm ²
Brine	Single-phase	0	43428	301	652	5015	3160
	Two-phase	0	86856	602	1304	10029	6319
Polymer	Both	1250	86856	602	1304	10029	6319

1. Terpolymer of acrylamide, hydrolyzed acrylamide and AMPS; 2. Mass of solute per million mass of solution.

Table 4. Summary of the measurement equipment used in the experiments and their purpose.

Equipment	Experiment	Measurement
Pressure sensor	Single- and two-phase	Pressure drop across the core
UV-spectrophotometer	Single-phase only	Polymer concentration in the effluents
Conductivity meter	Single-phase only	Tracer (salt) concentration in the effluents
Beaker	Single- and two-phase	Produced fluid volume
Scale	Single- and two-phase	Produced fluid mass

A core saturated with brine, at residual oil saturation (S_{or}), was used at the start of the two-phase experiments. Firstly, an oil injection took place, followed by a polymer flooding, and lastly, a brine injection was done. The adsorption did not need to be satisfied in the two-phase core flooding experiments because we did not use the conventional method to measure IAPV.

All the experiments were performed at constant injection rate, and each different fluid injection was done until steady state was observed for a long period. The steady state was determined in the two-phase experiment when the pressure had stabilized and no more oil was produced. For the single-phase experiment, steady state was considered when we observed pressure stabilization and produced concentrations of polymer and salt equal to the injected ones.

2.2 IAPV Measurement – Single-phase Polymer Injection with Tracer (Classic Method)

Dawson and Lantz proposed a method to measure the polymer IAPV in core-flooding experiments [4]. The method consists in the injection of a polymer bank in a core saturated with brine in the presence of an inert tracer. Polymer and tracer concentration in the effluents have to be measured periodically. The periodicity of the concentration measurements has to be enough so that multiple points of data are taken while polymer and tracer concentrations are raising (the more, the better). The IAPV is then estimated as the difference between the injected pore volumes of polymer and tracer breakthroughs. This difference needs to be taken in a threshold value. In our work, we used 5% of the normalized concentration as the point to estimate the IAPV. This calculation can be done using equation (1), and an example can be seen in Figure 4.

$$IAPV = BT_t - BT_p \quad (1)$$

where BT refers to the injected pore volume associated with the threshold concentration for breakthrough, t indicates tracer, and p indicates polymer.

This method can be used in cores that contain oil. However, the oil has to be in its residual saturation, and any droplet of oil that enters the production system will harm the measurements. Polymer flooding is known to reduce residual oil saturation in some cases [18], so we did not measure the IAPV by the conventional method in the two-phase experiments.

We only used the conventional method to measure the IAPV in the single-phase experiments. In our experiments, we used salts as tracers, UV-spectrophotometer to measure polymer concentration, and a conductivity meter to measure tracer concentration. Both the UV-spectrophotometer and the conductivity meter used in our experimental apparatus provided inline and online measurements, ensuring enough data to perform a quality measurement, as shown in Figure 4.

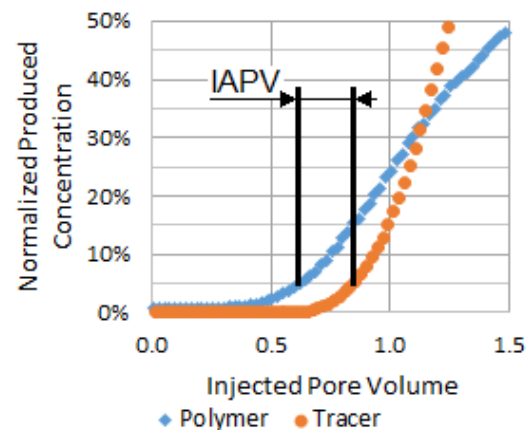


Figure 4. Example of IAPV calculation in a single-phase experiment using a graph of normalized produced concentration (produced concentration divided by injected concentration) of polymer (blue) and tracer (orange) by injected pore volume (injected volume divided by sample pore volume).

2.3 IAPV Measurement – Rheology-based Method (Alternative Method)

The method to measure polymer IAPV proposed in this paper is based on the *in-situ* viscosity of polymer. To measure the *in-situ* viscosity of a polymer, one should first be familiarized with the concepts of resistance factor (RF) and residual resistance factor (RRF). RF is a measurement of mobility reduction by the polymer solution relative to brine. RRF is a measurement of permeability reduction caused by the polymer solution as seen by a brine post-flush. RF and RRF are defined by equations (2) and (3), respectively.

$$RF = \frac{\Delta p_p}{\Delta p_w^{before}} \quad (2)$$

$$RRF = \frac{\Delta p_w^{after}}{\Delta p_w^{before}} \quad (3)$$

where Δp is the pressure differential, w indicates brine, and “before” and “after” superscripts are relative to the polymer injection. Note that the brine pressure differential before the polymer (Δp_w^{before}) denotes the pressure differential obtained in a virgin porous medium, i.e., before permeability reduction by polymer had taken place. It is worth noting that RF and RRF have to be measured only after steady state has been achieved, or they will be in error.

The polymer *in-situ* viscosity can then be estimated by equation (4) [19].

$$\eta_{p,is} = \frac{RF}{RRF} \cdot \mu_w \quad (4)$$

Where η denotes apparent viscosity, μ refers to Newtonian viscosity, and “is” indicates *in-situ*.

Since the *in-situ* viscosity was obtained through core flooding, it is associated with a flow rate or superficial velocity. Bulk viscosity estimated through rheometry is associated with shear rate. Therefore, to compare *in-situ* and bulk polymer viscosities, one needs a way to estimate the *in-situ* shear rate (i.e., shear rate experienced by the polymer inside the porous medium) in function of the superficial velocity (u). This can be achieved by Cannella’s model [20], represented by equation (5).

$$\dot{\gamma}_{p,is} = C \cdot \left(\frac{3 \cdot n + 1}{4 \cdot n} \right)^{\frac{n}{n-1}} \cdot \frac{u}{\sqrt{k \cdot \phi}} \quad (5)$$

Where $\dot{\gamma}$ is the shear rate, C is a scaling constant often assumed to be equal to 6, n is the power-law fluid behavior index, k is the permeability, and ϕ is the porosity.

Stavland et al. [8] developed an expression to calculate the polymer *in-situ* viscosity based on the IAPV. It can be expressed by equations (6) and (7).

$$\eta_{p,is} = \frac{\eta_{p,bulk} \cdot [1 + B]}{1 + B \cdot \sqrt{\frac{\eta_{p,bulk}}{\mu_w}}} \quad (6)$$

$$B = \frac{1}{(1 - IAPV)^2} - 1 \quad (7)$$

Note that the polymer *in-situ* ($\eta_{p,is}$) and bulk ($\eta_{p,bulk}$) viscosities have to be measured for the same shear rate. Since the polymer *in-situ* shear rate is difficult to control, one should do a bulk measurement in the same shear rate as the one experienced by the polymer *in-situ* ($\dot{\gamma}_{p,is}$). If we manipulate Stavland equations and isolate the IAPV, we come up with equation (8).

$$IAPV = 1 - \frac{\eta_{p,bulk} - \eta_{p,is} \cdot \sqrt{\frac{\eta_{p,bulk}}{\mu_w}}}{\eta_{p,is} \cdot \left[1 - \sqrt{\frac{\eta_{p,bulk}}{\mu_w}} \right]} \quad (8)$$

Therefore, we now have an expression to estimate the IAPV based solely on polymer *in-situ* ($\eta_{p,is}$) and bulk ($\eta_{p,bulk}$) viscosities, as well as water viscosity (μ_w).

Rheology-based method limitations / disadvantages over the classic method. Flexible polymers (e.g., HPAM) exhibit a shear-thickening behavior in porous media under high shear rates [8]. That is due to the viscoelastic behavior of the polymer and counteracts the depleted layer effect. Therefore, the *in-situ* rheology coupled approach can only be applied for flexible polymers flowing under medium to low shear rates. For rigid polymers (e.g., guar gum and hydroxyethylcellulose) and polymers with rigid structures (e.g., xanthan gum, schizophyllan, and scleroglucan), this shear-thickening behavior is absent, therefore, the model developed should be applicable in the full range of shear rates.

Another limitation is that the precision of the rheology-based method is directly related to the precision of the pressure sensor used to estimate RF and RRF. Therefore, pressure sensors used to estimate IAPV by this method should be as precise as possible.

One disadvantage is that on the classic method, the IAPV value is obtained by the breakthrough curves. Therefore there is no need to inject fluid until the steady state is reached. For the rheology-based method, RF and RRF measurements have to be taken under steady-state conditions.

Both the alternative and the classic methods require core flooding procedures, which require a lot of preparation and are time-consuming. In addition to that, the rheology-based method require the operator to perform bulk viscosity measurements at the same shear rate as the *in-situ* one. However, bulk polymer viscosity is well behaved (often adjusted by power-law models), so this is not a major disadvantage.

Polymer degradation can be a major issue for the rheology-based method. If the polymer degrades before or during the core flooding, the bulk rheological study have to be done with the degraded polymer. However, to reproduce the degradation of a polymer as it flows through a porous medium can be

difficult. Therefore, IAPV measurements using the alternative method in the presence of oxygen or in high shear conditions (low permeability or high injection flow rates) should be done with extra care to avoid oxidative and mechanical degradations, respectively.

Another disadvantage of the rheology-based model is the need to estimate the *in-situ* shear rate experienced by the polymer. There are several models to estimate this shear rate (the model proposed by Cannella [20] was used in this work). However, these models are dependent on core and fluid properties as well as some scaling factors (such as the constant C in Cannella's model), which can be difficult to define and may have a large variation.

Alternative approach advantages over the classic method. The classic method needs to satisfy the polymer adsorption, and then re-saturate the sample with brine before performing the polymer injection to measure IAPV. For the rheology-based method, the polymer solution can be injected in a virgin porous medium (100% saturated with brine or at s_{or}) and, after steady state is reached, the IAPV can be estimated.

One major advantage is related to the equipment. The rheology-based method only requires a pressure sensor, which is standard for core-flooding experiments. On the other hand, the classic method requires two pieces of concentration measurement apparatus, one for polymer and one for tracer. Related to that, the rheology-based method does not need the presence of a tracer and measurements are not affected by oil droplets in the production system. Also, the rheology-based method only requires the measurement of RF and RRF, while the classic method needs the produced concentration curve for polymer and tracer. Therefore, fewer data points have to be collected in the rheology-based method.

3 Results and discussions

Figure 5 presents the pressure differential curves for some of the experiments. Experiments TP-6 and TP-7 were previously reported by Silveira et al. [15] as experiments A3, and A4 respectively. In Silveira's work, the core-flooding experiments aimed to compare oil recovery by waterflooding and polymer flooding. In this work, we use some that experimental data to estimate IAPV in those two-phase experiments. For the single-phase experiments, the classic method calculation of the IAPV has been previously reported by Ferreira and Moreno [21]. In this work, we estimate the IAPV by the rheology-based (proposed) method and compare the results with the tracer-based (classic) ones.

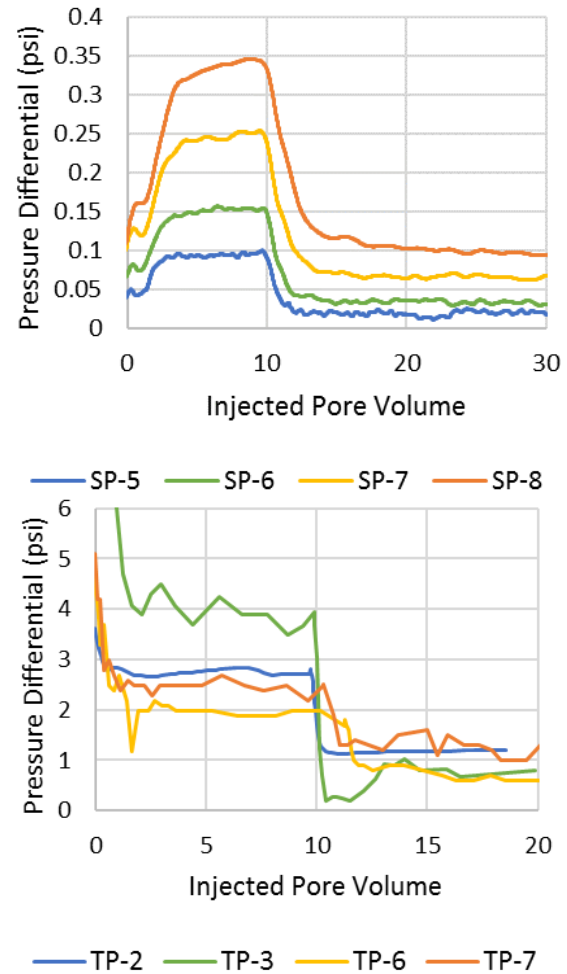


Fig. 5. Pressure differential data of some single- (top) and two-phase (bottom) experiments.

We applied the rheology-based method to estimate the IAPV from the pressure differential curves of all the experiments. Table 1 and

Table 2 compile the experimental conditions and the results of the two- and single-phase experiments, respectively.

3.1 Single-phase experiments (SP)

Both the proposed and the classic methods present a noisy behavior of the IAPV. Using the classic method, we obtained an average IAPV of 23.5% and a standard deviation of 4.3%, while the rheology-based method indicated an average IAPV of 26.2% and a standard deviation of 7.4%. The average values obtained by both methods are similar, with a relative difference of 11.5%. The rheology-based method tended to overestimate the IAPV value. The standard deviation values also indicate that the classic method was more reliable for our cases. Both methods indicate that the IAPV varies little with the flow rate.

Our injection system was composed of a syringe pump and a precision differential pressure sensor (error of 0.005psi). Therefore, the RF and RRF measurements are overall reliable. However, for the experiments with low flow rate (i.e., SP-1, SP-5, and SP-6), the differential

pressure measurement for the RRF is less than 10 times higher than the equipment uncertainty, so this may have propagated some error in the IAPV estimates.

Another reason for the differences between new and classic methods' results may be related to the model used to predict the IAPV through *in-situ* viscosity. Stavland's correlation [8] was developed and validated using different polymers and core permeability ranges. However, the Stavland's experiment-model correlation present some spread, as shown in Figure 6. Additionally, our work uses a polymer that was not included in Stavland's work, therefore some differences are expected. In fact, a previous works [21] showed that the polymer 5115SH displays a less shear-thinning *in-situ* behavior than the one forecasted by Stavland's model.

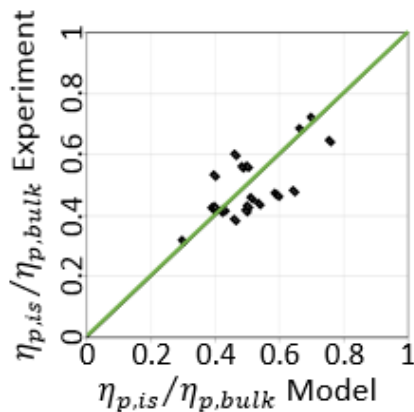


Figure 6. Stavland's results [8]: ratio between in-situ and bulk viscosities as measured experimentally versus predicted by the model of equation (7). A perfect correlation would match the green line (adapted from [8])

3.2 Two-phase experiments (TP)

The two-phase experiments show the same noisy behavior as the single-phase ones. The average IAPV obtained (rheology-based method) was 30.9% with a standard deviation of 8.4%. The average value showed an 18% relative difference to the single-phase values obtained by the same method. On average, the two-phase experiments resulted in a higher IAPV and had a higher standard deviation when compared to the single-phase ones.

One reason for the differences between single- and two-phase IAPV measurements may be associated with the reduction of residual oil caused by flexible polymers [18]. Silveira's work report that experiments TP-6 and TP-7 reduced the residual oil saturation when compared with waterflooding. This reduction can affect RF and RRF in different, and not accounted for, proportions. Consequently, the IAPV calculated by the rheology-based method can be influenced by the reduction of residual oil saturation.

The polymeric solution experienced higher shear rates in the two-phase core flooding than the single-phase ones (as high as $1300s^{-1}$). In these shear rates, some flexible polymers may exhibit a shear-thickening behavior [8]. However, this effect would have increased the RF and resulted in lower IAPV estimation by the rheology-based method. That would

have happened because the method would be applied outside its valid range of shear rates and would be in error. However, the effect observed was the opposite (i.e., IAPV was higher than expected), so the polymer probably did not exhibit shear-thickening behavior in our experimental conditions.

Table 5 presents the IAPV values of the two-phase experiments. The experiments were joined in groups regarding the temperature, sample size, oil type, back pressure presence, and iron removal. The experiments of higher temperature as well as the ones that had no iron removed indicated higher IAPV than their counterparts. However, we cannot confirm this due to the standard deviation associated with these groups. Sample size and back pressure presence did not seem to affect the IAPV measurements.

Table 5. Grouped IAPV measurements for the two-phase experiments.

	IAPV		Exp. Count
	Average	Std. dev.	
60°C ¹	35.1%	6.5%	3
23°C	28.4%	9.0%	5
Long sample ²	31.0%	10.1%	2
Short sample ³	30.9%	8.8%	6
Back pressure	29.5%	12.2%	3
No back pressure	31.8%	6.9%	5
Iron removal	24.5%	7.6%	2
No iron removal	33.1%	8.0%	6

1. Experiment TP-8 (55°C) was considered in this statistic; 2. Length >200mm; 3. Length ~60mm.

Conclusions

In this paper, we developed a new method for estimating the IAPV based on the *in-situ* viscosity of polymers. We validated the proposed method using a series of single- and two-phase experiments. The main conclusions are:

- The rheology-based technique is successfully able to predict polymer IAPV for single- and two-phase experiments alike. The relative difference in the results compared to the classic method (tracer-based) was of 11.5%;
- For flexible polymers, the new methodology is limited for mid to low shear rates, while according to the literature there should be no limitation for polymers with rigid structures.
- The reliability of the IAPV obtained applying the new method depends on the uncertainty of the pressure data;
- The main advantages of the proposed approach over the classic one are: fewer and simpler equipment are required, fewer data points are needed, there is no need to inject a tracer, and it is not affected by oil droplets in the production system;
- Reduction of the residual oil saturation by polymer flooding can affect the IAPV value determined by the proposed method. However, this will occur if the S_{or} reduction is enough to change RF and RRF measurements;
- Based on the experiments reported, flow rate, temperature, core size, pore pressure, and iron presence did not seem to affect the IAPV

measurements. Although higher IAPV was observed for higher temperature and higher iron content, we cannot confirm this dependency.

References

1. Sorbie, K. S. *Polymer-Improved Oil Recovery*, CRC Press, Boca Raton, Florida (1991), 359p.
2. Bondino, I. Nguyen, R., Hamon, G., Ormehaug, P. A., Skauge, A., Jouenne, S. "Tertiary Polymer Flooding in Extra-Heavy Oil: an Investigation Using 1D and 2D Experiments, Core Scale Simulation and Pore-Scale Network Models", *International Symposium of the Society of Core Analysts, Austin, Texas*, (2011), 12p.
3. Unsal, E., ten Berge, A. B. G. M., Wever, D. A. Z. "Low salinity polymer flooding: Lower polymer retention and improved injectivity", *J Pet Sci Eng*, (2018) **163**:671–682. doi: 10.1016/j.petrol.2017.10.069
4. Dawson, R., Lantz, R. B. "Inaccessible Pore Volume in Polymer Flooding", *Soc Pet Eng J*, (1972) **12**:448–452. doi: 10.2118/3522-PA
5. Moore, J. C. "Gel permeation chromatography. I. A new method for molecular weight distribution of high polymers", *J Polym Sci Part A Gen Pap*, (1964) **2**:835–843. doi: 10.1002/pol.1964.100020220
6. Sorbie, K. S. "Depleted Layer Effects in Polymer Flow through Porous Media", *J Colloid Interface Sci*, (1990) **139**:299–314. doi: 10.1016/0021-9797(90)90103-U
7. Omari, A., Moan, M., Chauveteau, G. "Wall effects in the flow of flexible polymer solutions through small pores". *Rheol Acta*, (1989) **28**:520–526. doi: 10.1007/BF01332923
8. Stavland, A., Jonsbraten, H., Lohne, A., Moen, A., Giske, N. H. "Polymer Flooding - Flow Properties in Porous Media versus Rheological Parameters", *SPE EUROPEC/EAGE Annual Conference and Exhibition, Barcelona, Spain*, (2010), pp 14–17.
9. Chauveteau, G., Zaitoun, A. "Basic Rheological Behavior of Xanthan Polysaccharide Solutions in Porous Media: Effects of Pore Size and Polymer Concentration", *Proceedings to the European symposium on EOR*, (1981), pp 197–212.
10. API, "Recommended Practices for Evaluation of Polymers Used in Enhanced Oil Recovery Operations", (1990), 74p.
11. Wan, H., Seright, R. S. "Is Polymer Retention Different Under Anaerobic vs . Aerobic Conditions?", *SPE J*, (2017), **22**:431–437. doi: 10.2118/179538-PA
12. Cardoso, O. R., Balaban, R. C. "Comparative study between Botucatu and Berea sandstone properties" *J South Am Earth Sci*, (2015), **62**:58–69. doi: 10.1016/j.jsames.2015.04.004
13. Appoloni, C. R., Fernandes C. P., Rodrigues C. R. O. "X-ray microtomography study of a sandstone reservoir rock" *Nucl Instruments Methods Phys Res Sect A Accel Spectrometers, Detect Assoc Equip*, (2007), **580**:629–632. doi: 10.1016/j.nima.2007.05.027
14. Ferreira, V. H. S., Moreno, R. B. Z. L. "Polyacrylamide Mechanical Degradation and Stability in the Presence of Iron" *OTC Brasil, Rio de Janeiro, Brazil*, (2017), 15p. doi: 10.4043/27953-MS
15. Silveira, B. M. O., Lopes, L. F., Moreno, R. B. Z. L. "Polymer Flooding in a High Salinity Heavy-Oil Reservoir", *Brazilian J Pet Gas*, (2018), **12**:35–51. doi: 10.5419/bjpg.2018-0004
16. Kamal, M. S., Sultan, A. S., Al-Mubaiyedh, U. A., Hussein, I. A. "Review on Polymer Flooding: Rheology, Adsorption, Stability, and Field Applications of Various Polymer Systems", *Polym Rev*, (2015), **55**:491–530. doi: 10.1080/15583724.2014.982821
17. Silveira, B. M. O., Lopes, L. F., Moreno, R. B. Z. L. "Rheological Approach of HPAM Solutions under Harsh Conditions for EOR Applications", *Int J Eng Technol IJET-IJENS*, (2016), **16**:1–8.
18. Vermolen, E. C. M., van Haasterecht, M. J. T., Masalmeh, S. K. "A Systematic Study of the Polymer Visco-Elastic Effect on Residual Oil Saturation by Core Flooding", *SPE EOR Conference at Oil and Gas West Asia, Muscat, Oman*, (2014). 14p. doi: 10.2118/169681-MS
19. Unsal, E., Oedai, S., Buijse, M., Humphry, K., van der Lee, M. "In situ Viscosity Measurements of Microemulsions in Cores with Different Permeabilities", *18th European Symposium on Improved Oil Recovery. Dresden, Germany*, (2015). 15p. doi: 10.3997/2214-4609.201412136
20. Cannella, W. J., Huh, C., Seright, R. S. "Prediction of Xanthan Rheology in Porous Media" *SPE Annual Technical Conference and Exhibition, Houston, Texas*, (1988). 16p. doi: 10.2118/18089-MS
21. Ferreira, V. H. S., Moreno, R. B. Z. L. "Impact of flow rate variation in dynamic properties of a terpolymer in sandstone" *J Pet Sci Eng*, (2017) **157**:737–746 . doi: 10.1016/j.petrol.2017.07.071