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REVIEW PAPER - PRODUCTION ENGINEERING

Oil displacement mechanisms of viscoelastic polymers in enhanced oil recovery (EOR): a review

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Abstract Polymer flooding has proved economically and technically successful in numerous enhanced oil recovery (EOR) projects, which can often increase oil recovery from 12 to 15 % of the original oil in place. When a reservoir is flooded with viscous polymer solution, the mobility ratio between the displacing fluid (i.e., water) and the displaced fluid (i.e., oil) becomes more favorable if compared to conventional water flooding. Therefore, the volumetric sweep efficiency and correspondingly the overall oil recovery are effectively improved. Currently, there is a widespread idea that polymer flooding is inefficient in improving the microscopic oil displacement (at pore scale). However, recent research based on laboratory studies and pilot field testing has proved otherwise. It seems that the viscoelastic properties of polymeric systems indeed improve the microscopic displacement efficiency of residual oil. This paper reviews and emphasizes the recovery mechanisms that have been proposed to explain oil displacement by polymer flooding within oil reservoirs. The aim of this review is to provide a synopsis of polymer flooding which is rapidly emerging as a popular and advantageous EOR process.

Keywords Enhanced oil recovery · EOR · Polymer flooding · Volumetric sweep efficiency · Microscopic displacement efficiency · Polymer viscoelasticity

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Introduction

As early as the 1960s, polymer flooding has been suggested as an oil displacement process in enhanced oil recovery (EOR), with the main functionality of increasing the viscosity of the displacing fluid, which is commonly water (Sandiford 1964). This pioneer work conducted by Sandiford was then followed by wide research efforts with the purpose of recognizing the benefits of using non-Newtonian displacing fluids in oil recovery applications (Szabo 1975; Dominguez and Whillhite 1977; Gleasure 1990).

For most oil reservoirs, a large amount of oil is left behind in the formation trapped within the rock, even after extensive water flooding due to the unfavorable mobility ratio between the driving (displacing) water and the displaced oil. Once a preferential flow path is formed within the porous media, the driving water will flow directly from the injection well to the production well bypassing the oil bearing zones, which ultimately causes a relative low oil recovery particularly in heavy oil reservoirs.

To reach the bypassed oil zones, viscous polymer solution is usually injected into the reservoir as the driving fluid, strategy that is well-known as polymer flooding, by which the poor mobility ratio encountered in conventional water flooding is corrected. Consequently, polymer flooding increases the volumetric sweep efficiency of the flooded reservoir.

Currently, polymer flooding is considered as one of the most promising technologies in EOR process because of its technical and commercial feasibility. Particularly, the interest on polymer flooding applications worldwide has been stimulated by the outstanding results reported from the large-scale polymer flooding application in the Daqing oil field in China, with incremental oil productions of up to 300,000 barrels per day (Wang et al. 2001a).

In practice, two commercial polymers, hydrolyzed polyacrylamides (HPAM) and xanthan gums, are commonly used in oil field applications. HPAM is a water-soluble polyelectrolyte with negative charges on the polymer chains. Xanthan gums, which are polysaccharides, show excellent viscosifying ability, high tolerance to salinity, and temperature (Guo et al. 1999).

The well-established relationship between capillary number and oil recovery using Newtonian fluids, indicates that a substantial increase in oil recovery at the pore level (micro-scale) in rock formations can be obtained if the capillary number is increased by several thousand times. However, in the case of polymer flooding (non-Newtonian fluids), this number is normally increased less than 100 times (Stegemeier 1977; Wang et al. 2000). Consequently, it has been suggested for long time that polymer flooding can only improve the volumetric sweep efficiency with no effect whatsoever on the microscopic displacement efficiency (Du and Guan 2004). Nevertheless, the fact that the oil recovery factor was increased during polymer flooding by up to 13 % of the original oil in place in the Daqing oil field, made researchers to rethink if this significant incremental oil recovery could be explained just by the promotion of enhanced volumetric sweep efficiency, or could also be explained by the simultaneous increased efficiency of the microscopic-scale displacement. Improvements of the microscopic sweep efficiency by polymer flooding could be attributed to the distinctive flow characteristic of polymer solutions due to their viscoelastic properties.

Thus, this paper reviews the oil displacement mechanisms taking place during polymer flooding operations. Specifically, it aims to explain the individual contributions of the viscous component and the elastic component of the polymer injected on the overall incremental oil recovery.

Overall oil displacement efficiency

The overall oil displacement efficiency during oil recovery processes is defined by the product of the macroscopic displacement efficiency (macro-scale) and the microscopic displacement efficiency (micro-scale). Macroscopic displacement efficiency is a measure of the effectiveness of the displacing fluid(s) in contacting the oil zone volumetrically; while microscopic displacement efficiency refers to the effectiveness of the displacing fluid(s) in mobilizing oil trapped at the pore scale by capillary forces. Therefore, any displacement mechanism that can improve either the macro-scale or micro-scale oil sweep efficiency during polymer flooding is beneficial to increment oil production (Romero-Zerón 2012).

Fluid mobility control

The primary purpose of polymers in EOR processes is to control the mobility of the displacing phase (i.e., water). Mobility is defined as the ratio of the relative permeability of the fluid (i.e., water or oil) to the viscosity of the same fluid. The importance of controlling fluid mobility to increase macroscopic displacement efficiency has been well recognized by many researches (Pitts et al. 1995; Du and Guan 2004; Kotlar et al. 2007). The addition of polymer to the displacing phase (i.e., water) reduces its mobility by thickening the aqueous phase and significantly diminishing the formation of viscous fingerings and/or channels. A simultaneous mechanism taking place during polymer flooding is the reduction of the relative permeability to the displacing phase caused by the retention of polymer (adsorption and mechanical retention) within the porous media. Therefore, polymer flooding is very effective in improving the volumetric sweep efficiency.

Mobility ratio (M) is an important and useful parameter to quantify the mobility contrast between the displacing fluid (i.e., water) mobility and the displaced phase (i.e., oil) mobility. Thus, the mobility ratio for a waterflood is given by the following expression (Eq. 1) (Pitts et al. 1995):

$$M = {}^{\lambda_{\mathrm{w}}}\!/_{\lambda_{\mathrm{o}}} = \frac{k_{\mathrm{rw}}/\mu_{\mathrm{w}}}{k_{\mathrm{ro}}/\mu_{\mathrm{o}}} = \frac{k_{\mathrm{rw}}\mu_{\mathrm{o}}}{k_{\mathrm{ro}}\mu_{\mathrm{w}}} \tag{1}$$

where λ is the fluid mobility, k_{r} is the relative permeability, and μ is the fluid viscosity; the subscripts w and o denote water phase and oil phase, respectively.

The displacing fluid mobility should be equal or less than the total mobility of the displaced multiphase fluids (Sheng 2011; Lake 1989; Dyes et al. 1954). Figure 1 shows relative mobility as a function of water saturation. The plot indicates the individual mobility of water and oil, and the total mobility (λ_{t}), which is the summation of water and oil mobilities. The minimum total relative mobility, which corresponds to the minimum value of λ_{t} on the total mobility curve (λ_{t} at the corresponding S_{w}), is also indicated in Fig. 1.

In some cases, the total mobility of the fluids can not be calculated because the mobile fluid saturations are unknown; in these situations the minimum total mobility is often used to determine the target viscosity required for polymer flooding (Gogarty 1969; Gogarty et al. 1970).

The conventional concept of mobility ratio distinguishes "favorable" mobility conditions when $M \le 1$ and "unfavorable" mobility conditions when $M > 1$. However, Sheng (2011) recently demonstrated that this existing concept of mobility ratio is invalid and proposed an updated definition of mobility ratio expressed as the ratio of the displacing fluid mobility to the oil mobility

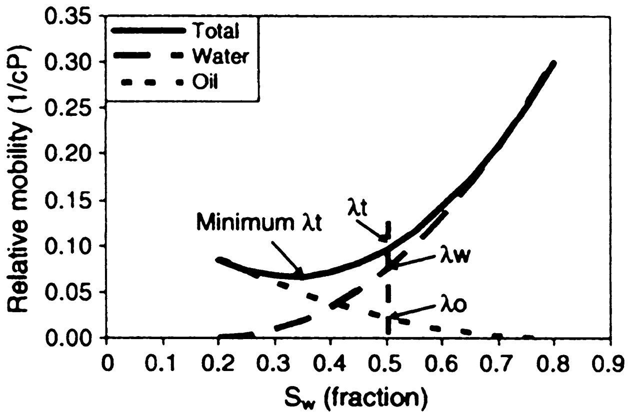

Fig. 1 Relative mobility as a function of saturation of water (source: Sheng 2011)

multiplied (corrected) by the normalized movable oil saturation ($\bar{S}_o$) as indicated by Eq. (2)

$$M = {}^{\lambda_w}\!/_{\lambda_o}\bar{S}_o = \frac{k_{rw}/\mu_w}{k_{ro}/\mu_o}\bar{S}_o = \frac{k_{rw}\mu_o}{k_{ro}\mu_w}\bar{S}_o. \qquad (2)$$

This new definition of mobility ratio was demonstrated by numerical simulation validated using coreflooding data available for polymer flooding and alkali–surfactant–polymer. According to Sheng (2011), this new definition of mobility ratio should be used to determine the concentration of the mobility control agent (polymer) to be applied in the field.

Disproportionate permeability reduction (DPR)

Polymer solutions can reduce the mobility of the displacing phase by two mechanisms: by increasing the viscosity of the displacing phase and by causing disproportionate permeability reduction (DPR); i.e., polymer or gel considerably reduces water relative permeability (k_{rw}), while producing minimum reduction in the oil relative permeability (k_{ro}) (Schneider and Owens 1982; Taber and Martin 1983; Niu et al. 2006). The following mechanisms have been proposed to explain DPR: (1) segregation of flow pathways (water and oil); (2) shrinking/swelling of polymer depending on phase flow; (3) layer formation on pore wall by adsorbed polymer; and (4) wettability alteration (Mennella et al. 1998; Liang and Seright 1997; Nilsson et al. 1998; Barreau et al. 1997; Zaitoun and Kohler 1988). Among these mechanisms, polymer adsorption (layer formation) and segregation of flow pathways have been considered as the dominant mechanisms for DPR when polymers solutions (without cross-linker) are used.

Zheng et al. (2000) proposed an empirical model to correlate the reduction of relative permeability with polymer adsorption. They found that the adsorption of hydrolyzed polyacrylamides on both water-wet and mild oil-wet cores induces a selective reduction of the relative permeability to water with respect to the relatively permeability to oil. In the mild oil-wet core case, wettability change was also considered to be another mechanism for the reduction of the relative permeability to water. Córdova et al. (2002) observed selective permeability reduction due to adsorbed nonionic polyacrylamides on mica; however, wettability alteration was not detected in this study.

Al-Sharji et al. (2001) presented a visualization study showing the built-up of cationic polyacrylamide polymer layers on the grain crevices in water-wet models. Based on this work, the adsorption-entanglement mechanism or the dynamically formed layer of polymer was proposed to explain DPR. However, in the oil-wet case, DPR was not observed (Elmkies et al. 2001). This mechanism (adsorption-entanglement) is also applicable for the adsorption of anionic polyacrylamides, which are extensively used in oil fields (Grattoni et al. 2004; Ogunberu and Asghari 2005).

In addition, Denys et al. (2001) proposed a bridging adsorption mechanism for cationic polyacrylamides when polymer macromolecules are stretched under high rates. This mechanism was further investigated by Chauveteau et al. (2002).

Nilsson et al. (1998) and Stavland and Nilsson (2001) proposed another mechanism "the segregated flow path of oil and water at the pore level" to explain DPR during polymer flooding. Currently, it is normally considered that DPR occurs due to the combined action of several mechanisms. Nevertheless, few experimental works clearly demonstrated that polymer adsorption onto rock surface is the dominant mechanism for inducing DPR.

Polymer elasticity and/or flow resistance

Flow resistance is the third mechanism that can improve volumetric or macroscopic sweep efficiency during polymer flooding. Dehghanpour and Kuru (2010) investigated the effect of viscoelastic fluid rheology on the formation of an "internal cake" (frictional pressure drop). They observed that the fluid with higher elasticity exhibited significantly higher pressure drop during flow through porous media. This elastic effect that results in additional pressure drop could be enhanced by widening the molecular weight distribution without changing the shear viscosity. A similar trend was obtained by Urbissinova et al. (2010), who also evaluated the contribution of polymer's elasticity in EOR. Likewise, they observed that the polymer solution showing higher elasticity experienced higher flow resistance (pressure drop) to flow through porous media than the polymer with lower elasticity, even though their shear viscosities were identical, which rendered improved macro-scale sweep efficiency and oil recovery (Veerabhadrappa 2012). This mechanism may also improve the microscopic displacement efficiency in displacing residual oil immobilized in the core by capillary forces and rock configuration (Wang et al. 2000).

In the last decade, it has been proposed that polymer flooding can also increase the microscopic displacement efficiency by mobilizing and displacing residual oil saturation (trapped by capillary forces). This phenomenon has been attributed to the elasticity of the polymer solutions (Wang et al. 2000). This proposition has generated controversial arguments (Bakhitov et al. 1980; Schneider and Owens 1982; Pusch et al. 1987; Zaitoun and Kohler 1987, 1988).

Nonetheless, Wang et al. (2000) have studied this issue extensively by evaluating the effectiveness of polymer flooding in displacing "residual oil" after water flooding at different conditions as follows. (1) Residual oil in "dead ends"; (2) residual oil films on rock; (3) residual oil in pore throats trapped by capillary forces; 4) residual oil unswept in micro-scale heterogeneous portions of the porous media. In all cases, Wang et al. (2000) observed that residual oil was reduced after polymer flooding. Xia et al. (2008a) used a theoretical and an experimental approach to investigate the effect of the elastic characteristics of the driving fluid on the microscopic displacement efficiency. The results show that viscoelastic polymer solutions are efficient in displacing different types of residual oil without even increasing the pressure gradient. In contrast, Huh and Pope (2008) pointed out that a tertiary polymer flooding did not reduce the water flooding residual oil saturation in an homogeneous, water-wet Berea sandstone core and in Antolini core with small-scale heterogeneity, but a secondary polymer flooding did displace oil below the residual oil saturation. Hou et al. (2009) observed the increase of microscopic displacement efficiency in a polymer flooding using an industrial CT system and argued that the essence of this phenomenon is that polymer flooding increases the oil/water mobility ratio and diverts the flow profile of the displacing fluid that causes the redistribution of oil saturation. The combination of the effects of diverted waterways and polymer viscoelasticity mobilizes and displaces the residual oil. Cheng et al. (2010) analyzed the distribution of residual oil in the Daqing oil field after polymer flooding. They determined that the thickness of the volume of the reservoir contacted by polymer was increased by 21.4 % and that oil saturation was reduced to 11.9 % as compared to water flooding. The residual oil saturation after polymer flooding in the Daqing oil field is mainly controlled by capillary forces. Chen et al. (2011) modeled polymer flooding from the Daqing oil field. In this work, the mechanism of polymer elasticity was introduced. The field production performance of polymer flooding was matched, and the results suggested that high concentration polymer flooding cannot only enhance volumetric sweep efficiency, but also increased microscopic displacement efficiency. Meybodi et al. (2011) used an image processing technique to analyze and compare microscopic and macroscopic displacement behaviors during polymer flooding in oil-wet and water-wet porous media. They concluded that a favorable microscopic displacement could enhance the macroscopic sweep efficiency in strongly water-wet medium, but in a strongly oil-wet medium, there are more factors that influence the microscopic displacement, front stability, and oil recovery.

Mechanisms enhancing microscopic displacement efficiency

The proposed mechanisms to explain the enhancement of the microscopic displacement efficiency during polymer flooding are briefly reviewed in the subsequent paragraphs.

Pulling effect mechanism

Wang et al. (2007, 2011) indicated that if a fluid with elastic properties flows over dead ends, normal stresses between oil and polymer solution are generated in addition to the shear stresses resulting from the long molecular chains. Thus, polymer imposes a larger force on oil droplets and pulls them out of dead ends. The amount of residual oil pulled out from dead ends is proportional to the elasticity of the driving fluid; these observations are presented in Fig. 2.

The viscoelastic polymer (HPAM) pushes the fluid ahead and pulls the fluids besides and behind, while the non-elastic fluids (water and glycerin) as presented in Fig. 2 are capable of pushing the fluids ahead but cannot "pull" out oil from the dead end.

Likewise, Luo et al. (2006) compared the effect of polymer elasticity on microscopic oil displacement efficiency. Figure 3 displays the pictures of the experiments carried out in a dead end pore (glass-etched model), in which displacing fluids having different viscoelastic properties were injected over the dead end to displace the trapped oil. The ratio of the elastic modulus (G') to the viscous modulus (G'') is useful to represent the elasticity of a fluid. In this experiment, the dead end pore model was flooded with solutions with increasing elasticity and/or increasing G'/G'' values (0, 0.92, 1.75, and 2.72). The residual oil saturation after water (i.e., non-elastic fluid) injection over the dead end is shown in Fig. 3a, and the saturation of residual oil after water flooding followed by polymer flooding is shown in Fig. 3b, c. It can be seen that

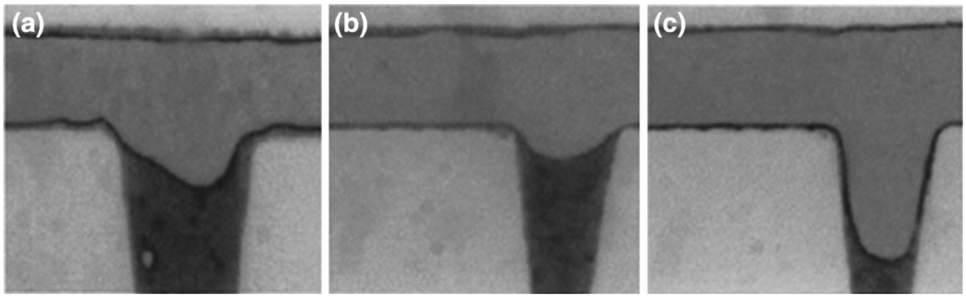

Fig. 2 Residual oil (*darker color*) in "dead ends" after **a** water, **b** glycerin, and **c** HPAM floods (source: Wang 2001)

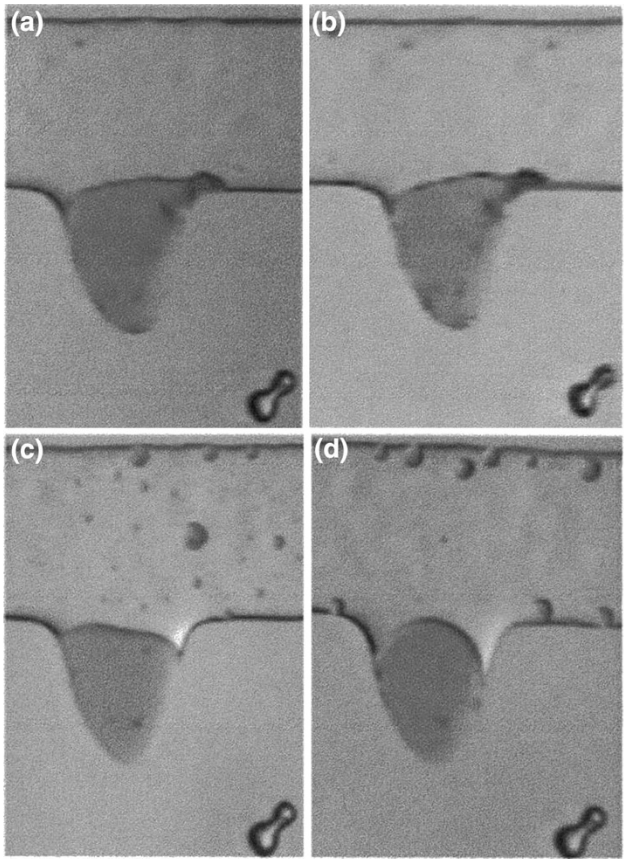

Fig. 3 Distribution of residual oil by water and polymer solutions with different viscoelastic properties: **a** $G'/G'' = 0$, $E_D = 0.0$; **b** $G'/G'' = 0.92$, $E_D = 0.0$; **c** $G'/G'' = 1.75$, $E_D = 0.13$; **d** $G'/G'' = 2.72$, $E_D = 0.18$ (source: Luo et al. 2006)

an increase in the elasticity of the displacing fluid decreases the saturation of the oil trapped in the dead end pore.

This effect has been further investigated through numerical simulation of polymer flooding over dead ends (Yin et al. 2006, 2012; Xia et al. 2008a, b; Zhang and Yue 2008). The pulling effect also works for residual oil trapped in a configuration that have both ends open to flow. This type of residual oil is immovable mainly because of capillary forces. In this case, there is at least a 50 % chance that the capillary force retaining the oil droplet can be reduced by the pulling effect (Wang et al. 2000).

Stripping mechanism

In oil-wet porous media, residual oil is attached to the rock surface in the form of a continuous oil film. Wang et al. (2000) reported the velocity profile of Newtonian and non-Newtonian fluids in capillary tubes and observed that the velocity gradient near the capillary wall for elastic fluids is considerably greater than for Newtonian fluids. Therefore, a stronger force is produced during flow of polymer solutions as compared to water, enhancing stripping oil films off the rock surface which eventually leads to a promotion of oil displacement efficiency (Jiang et al. 2008; Xia et al. 2004, 2008b; Wang 2001; Wang et al. 2001c; Sedagha et al. 2013). The alteration in wettability from oil-wet to more water-wet due to this oil stripping effect would also increase oil recovery.

Oil thread or column flow mechanism

The third possible mechanism bearing on the elastic property of polymers is oil thread flow. Elastic polymer solutions are able to stabilize oil threads due to the normal stress. As Wang et al. (2001a, c) and Luo et al. (2006) observed, oil is pulled by the polymer solution into oil columns and then forms oil threads as they aggregate with residual oil downstream. The normal force acting on the convex surface of the oil thread is supposed to be larger than the normal force acting on the concave surface. Thus, the essential function of the normal stress is to prevent oil threads from deforming, which potentially improves the displacement efficiency (Sedagha et al. 2013). Moreover, this force contrast increases with the Deborah number (N_{Deh}), which is a dimensionless number commonly employed to describe the elasticity of polymer solutions in porous media. In regards to this mechanism, Huh and Pope (2008) indicated the possibility that the interfacial tension between oil and polymer solution could destabilize the long oil column and break it into oil droplets. However, the elasticity of polymer solutions could resist this interfacial deformation. Thereby, the oil column could be either drained to a thinner cross-section causing it to break it up into smaller ganglia, which results in lower residual oil saturation, or the thinned oil column could be broken into longer-length oil ganglia that have more chance to be mobilized.

Shear thickening effect

Theoretically, the rheological behavior of polymer solutions as a function of shear rate (flow velocity gradient) in porous media could be divided into three types: Newtonian, shear thinning, and shear thickening. When polymer molecules flow through a series of pore bodies and pore throats, the flow field undergoes elongation and contraction. Shear thickening occurs only when polymer solutions flow through porous media and the flow velocity is too high that the polymer molecules do not have sufficient relaxation time to stretch and recoil to adjust to the flow velocity and the elastic chains cause a high apparent viscosity (shear thickening). This behavior can help driving fluid to rapidly displace the mobile but hard to displace oil or to displace the bypassed oil in small-scale heterogeneities more effectively (Delshad et al. 2008). Therefore, the shear thickening effect is considered as one of the possible mechanisms for the enhanced microscopic displacement efficiency during polymer flooding. A simple analysis elaborating on this point has been made by Jones (1980). Moreover, the high apparent viscosity is also beneficial for improvement of macro-scale sweep efficiency (Seright et al. 2010).

Although, shear thickening behavior is an important polymer flow regime in polymer flooding, it is still a challenge to accurately describe it. The reason is that this behavior cannot be quantified through bulk rheological measurements even at comparable shear rates, as is the case for the shear thinning regime (Green and Willhite 1998). To quantify this flow behavior, several models or equations have been proposed (Hirasaki and Pope 1974; Masuda et al. 1992; Chen et al. 1998). Recently, more reliable and precise predictions of the shear thickening regime in terms of the apparent viscosity (pressure drop) dependence on the effective shear rate (flow velocity) have been developed. Garrocuh and Gharbi (2006) proposed an empirical viscoelastic model analogous to Darcy's law to study the flow behavior of HPAM and Xanthan gum in porous media. This model accounts for polymer elasticity, viscosity, and porous media structure (porosity and permeability). This study shows that the Deborah number may not be an adequate parameter to characterize viscoelastic flow in porous media. Instead, a dimensional number called "viscoelasticity number" (N_v) seems to be more adequate because it clearly distinguishes viscous flow from viscoelastic flow. This model may allow predicting the relationship between pressure drop and flow velocity in the shear thickening regime.

Delshad et al. (2008) established another model for HPAM polymer solutions. One notable distinction of this model when compared with previous models is that the shear thickening viscosity does not increase indefinitely with the Deborah number and a plateau value is reached, which seems more reasonable. Delshad et al. (2008) also attempted to combine equations for the shear thinning regime and the shear thickening region to obtain a viscoelastic model applicable to the entire shear rate range. This model accounts for both rheological behaviors and was successfully used to history-matched data taken from published laboratory reports. Kim et al. (2010) used this viscoelastic model to develop a database for HPAM polymer solutions for a wide range of polymer concentration, salinity, and hardness, and temperature making it more practical to quantify the apparent viscosity of the polymer solution at reservoir conditions. Recently, further improvement of the parameters of this model was presented by Sharma et al. (2011).

A constitutive equation was first developed by Zhang et al. (2011) to represent the viscoelastic behavior of HPAM solutions in porous media. This equation indicates that the increase in viscosity due to elasticity is proportional to the relaxation time, particle diameter, porosity, and it is inversely proportional to the Darcy velocity and the square root of tortuosity. This constitutive equation gives satisfactory agreement between calculated and experimental values, which validates its applicability for quantifying shear thickening behavior in porous media.

Cheng and Cao (2010) divided the flow performance of polymer solutions through porous media into three stages: entrance constriction, pore passage, and extrusion. Therefore, pressure drop could be built individually combining viscous drop and elastic drop, which allows establishing a constitutive model of viscous-elastic fluid in porous media that considered the polymer's flow characteristics and the porous media's features. This new model was tested against experimental data obtained from coreflooding, and accurately characterized the polymer solution's rheological behavior in porous media including the shear thinning and the shear thickening regimes.

Likewise, Stavland et al. (2010) and Norris (2011) presented a comparable but simpler rheological model that also covered the shear thinning and shear thickening viscosity regions. Unexpectedly, this model showed that the apparent viscosity decreased beyond the shear thickening regime with increasing shear rate during coreflooding tests. This phenomenon could be interpreted by the mechanical degradation of the polymer molecular structure caused by chain rupture. Thereby, an improved rheological model multiplied by a degradation term was proposed that can be effectively used to predict viscosity change in porous media.

Conclusions

The primary objective of this paper was to review the oil displacement mechanisms of polymer flooding aiming to provide an up to date overview of this topic. Based on the discussion presented, the following conclusions can be made:

1. At the macro-scale, polymer flooding improves the sweep efficiency by reducing the mobility ratio between the displacing phase and the displaced phase through increasing water viscosity and selectively decreasing the relative permeability to water (DPR effect).
2. DPR effect due to polymer flooding is strongly dependent on the porous media characteristics. In strongly oil-wet porous media, DPR is much less pronounced as compared to water-wet porous media. Polymer adsorption onto rock surface seems to be the dominant mechanism for inducing DPR.
3. At the micro-scale, polymer flooding improves displacement efficiency due to the elasticity of the polymer solution.
4. The pulling effect, oil stripping, oil thread and/or column flow, and polymer shear thickening mechanisms have been proposed to explain the enhanced microscopic displacement efficiency taking place during polymer flooding. However, more research is required to verify these mechanisms or to explore other possible explanations.

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