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Effect of porous media properties on the onset of polymer extensional viscosity

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ABSTRACT

Based on experimental results, it has been observed that, although the applied polymer solutions in EOR generally demonstrate shear thinning properties in rheometer, in porous media above a critical flow rate, apparent viscosity increases. This behavior is interpreted as the consequence of both elastic properties of polymer solution and rock properties. In this study, elastic properties of polymer solution is imported into numerical simulation by using modified form of the Carreau model and only effect of rock properties on the onset of extensional viscosity are studied. Results proved that for a more tortuous rock sample, extensional viscosity happens at a lower Darcy velocity. To define the onset of extensional viscosity, Deborah number explanation ($De=\varepsilon\tau_r$) is applied. A linear correlation is proposed as the relationship between stretch rate and Darcy velocity, in which the linearity coefficient is related to the tortuosity of rock sample. By calculating the stretch rate using this modification, De at the onset of extensional viscosity is the same for all rock samples. Furthermore some microscopic properties of pore geometries such as aspect ratio and length of pore throat are studied by using simplified 2D contraction–expansion channels. Initially the simulation is well validated by using experimental results reported by Chauveteau (1981). By increasing the aspect ratio, the onset of extensional viscosity occurs at lower Darcy velocity as polymer molecules are being exposed to larger stretch rate values. On the other hand by increasing the length of contracted part, the onset of extensional viscosity happens at higher Darcy velocity. This is due to the fact that polymer molecules have more time to be relaxed after being deformed due to the contraction channel.

1. Polymer extensional viscosity in porous media

The life of an oil reservoir can go through three distinct phases of field development, where in each phase different techniques are applied to maintain the highest level of oil production. Generally oil production from a reservoir is started by natural reservoir energies such as gas cap drive. However after some stages, the reservoir becomes depleted and cannot provide enough oil in economical level. Thereby, during secondary phase, water or gas injection is recommended to both maintain the reservoir pressure and sweep oil to the production wells. Due to reservoir heterogeneities and unfavorable mobility ratio, high amount of oil will be bypassed. Generally after primary and secondary stages of oil recovery, only 30–40% of initial oil in place will be recovered and large amount of oil will remain in reservoir. Thereby, as the third stage of field development, several techniques are proposed which are generally known as enhanced oil recovery (EOR) methods. In the other word, EOR methods attempt to recover oil beyond the secondary phase and target the oil which is either trapped by capillary forces or being bypassed and hard to recover. The EOR methods can be divided into four main categories: (a) thermal (e.g. combustion), (b) chemical (e.g. polymer flooding), (c) gas injection (e.g. CO_2 injection) and (d) the other methods which cannot be classified in the above mentioned categories (e.g. microbial).

Polymer flooding is a mature EOR technology, in which, polymer is applied to increase the viscosity of injecting water and reduce viscous fingering. In the other words, the main idea in using this EOR method is to increase volumetric sweep efficiencies, both areal and vertical sweep. Thereby the theoretical ultimate oil recovery in polymer and water flooding is the same (Lake, 1989; Stegemeier, 1974) and equal to $1-S_{wi}-S_{or}$. Although several experimental results revealed that polymer solution is not able to increase the microscopic displacement efficiency and it can only improve the macroscopic sweep efficiency and quicker oil production (Buchgraber et al., 2011; Farouq and Thomas, 2000; Pusch

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et al., 1987; Seright et al., 2009) recently some experimental results (Urbissinova et al., 2010) along with numerical studies (Afsharpoor and Balhoff, 2013; Bai et al., 2011; Xia et al., 2008) and CT image visualization (Hou et al., 2009; Meybodi et al., 2011) demonstrated that in some cases, the polymer can also mobilize the trapped oil (Bakhitov et al., 1980; Cheng et al., 2010; Sherbone et al., 1967; Wang et al., 2001b; Wu et al., 2007). Several reasons are proposed to explain this observation such as polymer adsorption (Zaitoun and Kohler, 1987, 1988), viscoelastic effect (Huifen et al., 2004; Wang et al., 2000, 2001a, 2001b; Wu et al., 2007), shear thickening (Delshad et al., 2008; Jones, 1980) and memory effect (Hossain et al., 2009). However, phenomena such as shear thickening and memory effect can be also considered as viscoelastic effects. Although the role of viscoelasticity in mobilizing trapped oil still remains vague, it is generally considered as the widely accepted reason for residual oil reduction.

Viscoelastic fluid is a type of fluid which demonstrates both viscous and elastic properties. One of the parameters which can be used to characterize the viscoelasticity of polymer solution is the relaxation time. It is widely used for interpretation of viscoelastic behavior, especially in porous media. It refers to the characteristic time required for the polymer molecules to be relaxed from a deformed state to its equilibrium configuration. Several methods are proposed for the measurement of polymer relaxation time (Castelleto et al., 2004; Lee et al., 1995).

Non-Newtonian fluid flow through porous media is a topic of great interest and it has a wide range of industrial applications. Several attempts have been made to study the behavior of non-Newtonian fluid in porous media both experimentally and numerically (Di Federico et al., 2014). In spite of extensive studies, universally accepted models which can be able to predict the non-Newtonian fluid behavior have not been developed yet. The main source of failure is that the complex behavior of non-Newtonian fluid cannot be accurately described by a limited number of averaged parameters in current rheological models. Meanwhile the behavior of polymer solution can be different when being exposed to pure shear flow and pure stretch flow and normally polymer solutions demonstrate higher resistance toward stretching flow. In addition to that, porous medium is a very complex geometry which made studying of polymer behavior more complicated.

The rheological behavior of viscoelastic polymer solution in porous media can be different from its behavior in rheometer. Generally polymer solutions which are used in polymer flooding such as Xanthan and HPAM demonstrate shear thinning properties in rheometer while based on experimental results (Chauveteau, 1981) it has been observed that for instance for HPAM, above a critical flow rate apparent viscosity increases. This phenomenon is interpreted as polymer viscoelastic effect. In other words, experimental results revealed that above a critical flow rate, the required energy to inject viscoelastic fluid into packed beds is higher than value predicted by viscometric measurements (Kemoblowski and Dziubinski, 1978). The behavior of viscoelastic polymer solution in porous media is schematically demonstrated in Fig. 1.

Several attempts have been made to explain this phenomenon in the molecular level such as the transient network model (Choplin and Sabatie, 1986) and the Coil-stretch model (De Gennes, 1974). The first model is generally applied to explain shear thickening behavior in rheometers, without considering the effect of porous media configurations, while in the second model, porous media properties are also taken into account. Polymer molecules are considered as spherical coil structures. Due to the contraction–expansion nature of porous media, the polymer molecules are both sheared (near the walls) and stretched (along the flow axis). When it is exposed to the stress, it will be deformed to conform to the applied stress. Therefore, the deformed polymer molecules

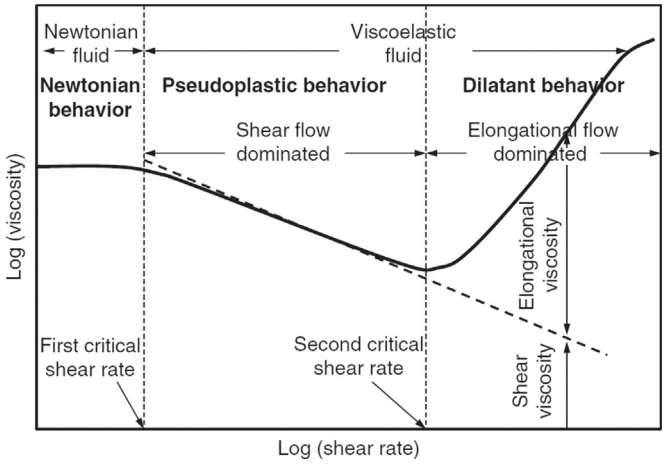

Fig. 1. Schematic demonstration of viscoelastic fluid flow behavior in porous media.

generate significant elastic energy which can be quantified by the normal stress difference (N_1) value.

Extensional viscosity is mainly considered as the consequence of the elastic nature of polymer solution when it is stretching. Therefore, for studying extensional viscosity, polymer molecules should be exposed to pure elongational flow. Although several techniques are developed to generate pure elongation flow experimentally in rheometers such as, lubricant planar, stagnation die flows and opposed jet devices, differentiating between shear rate and stretch rate is quite sophisticated in porous media as they occur simultaneously regarding to the tortuous nature of porous media. Therefore, instead of stretch rate in some studies other terms are used such as shear rate and deformation rate. Consequently this phenomenon is also called by different names such as extensional viscosity, elongational viscosity, shear thickening, viscosity enhancement, dilatant behavior and viscoelasticity.

As mentioned earlier, extensional viscosity is the consequence of both polymer and porous media properties. By considering only polymer solution relaxation times regardless of the media properties where the fluid is flowing through, the onset of extensional viscosity cannot be defined properly. When a polymer solution is passing through a porous medium, polymer molecules are exposed to several contraction–expansion channels. Consequently, polymer molecules are accelerated and decelerated due to variation of the channel cross sections. If time period between two successive rotations is long enough so that the polymer molecules can return to their original state, no extensional viscosity happens. Otherwise, if time for passing from one contraction to the other is less than the polymer relaxation time, then polymer molecules remain extended and extensional viscosity is observed. For characterizing the onset of extensional viscosity in porous media Deborah number explanation is widely applied. Deborah number considers the effects of both polymer and porous media properties and it is defined by the ratio between the polymer relaxation time and porous media characteristic time.

$$N_{De} = \frac{\tau_r}{\tau_E} \tag{1}$$

Practically, the onset of extensional viscosity plays a major role on polymer flooding design due to injectivity and trapped oil mobilization. Due to the importance of this parameter, several attempts have been made to capture the De number value at the onset of extensional viscosity as accurate as possible. In spite of several attempts to calculate the De number at the onset of extensional viscosity, a wide range of De is proposed (0.1–10) in the literature (Colby et al., 1991; Haas and Durst, 1982; Heemskerk