

Microscopic Roles of “Viscoelasticity” in HPMA polymer flooding for EOR

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Abstract A polymer solution with a transient network structure due to the entanglement of long chain molecules exhibits a viscoelastic behavior when it flows through a tortuous and diverging/converging channel in porous media. A constitutive equation is first developed to represent the viscoelastic behavior of polymer solutions in this article. Then a 3D viscoelastic polymer flooding model is established to examine the effect of elasticity of polymers on EOR (enhanced oil recovery). The model is validated in comparison with laboratorial coring data. The simulated results show that the oil recovery of viscoelastic polymer flooding can be enhanced by larger displacement efficiency due to its microscopic roles. In the meanwhile, the injection pressure required increases correspondingly if the elastic effect is significant. Relaxation time as a major characteristic parameter of viscoelastic polymer plays a decisive role, and therefore the HPAM (partially hydrolyzed polyacrylamide) with evident elastic property is recommended in chemical flooding.

Keywords Viscoelastic · Porous media · Constitutive equation · HPAM · EOR

Abbreviations

HPAM Partially hydrolyzed polyacrylamide

EOR Enhance oil recovery

1 Introduction

Most oil fields in China have experienced a certain period of water flooding and entered later stage of exploitation, during which the oil recovery was considerably reduced due to high viscosity of oil in such a high water-cut well (Han 1999). With water flooding applied, 60–70%

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of crude oil, i.e., residual oil were still retained in the reservoir (Shen 2000) and then polymer is added in the injected water in most operations to enhance oil recovery (EOR) (Littmann 1988). Polymer flooding now is becoming one of the most commonly used techniques in chemical flooding.

In the field of petroleum engineering, the dominant view on EOR mechanism in polymer flooding is that the polymer solutions injected into the reservoir turns out a kind of viscous fluid, which may lead to the viscosity growth of driving liquid, the permeability reduction of aqueous phase and then effective adjustment of mobility ratio between crude oil and flooding fluid. As a result, viscous fingering phenomenon frequently occurring in water flooding is avoided or mitigated to a certain degree (Littmann 1988). The facts are also responsible for the expansion of volumetric sweep efficiency macroscopically. Guo (1990) further explored the mechanism of polymer flooding by micro-seepage experiment, finding that additional acceptable mechanism is the greater shear stress between polymer solutions and oil than that between water and oil. Recent polymer flooding experiments further showed that HPAM (partially hydrolyzed polyacrylamide) solutions sometimes display some elastic behavior when passing through the natural and artificial cores. And such kind of viscoelastic polymer solutions may improve micro-displacement efficiency. Therefore, the study of mechanism of polymer flooding arouses people's attention once again.

As early as in 1970, Smith (1970) and Acharya (1986) had recognized viscoelastic effects of polymer liquids. They found that when polymer solutions flow through the porous media, it tends to display viscoelastic effects. Bird et al. (1987) and Marrucci (1975) described the extensional flow behavior of linear, flexible polymers by simple dumbbell model, which is later found to be incapable of describing a wide range of experimental data, especially those obtained for large extensional flow of dilute polymer solutions. Warner (1982) proposed a finite-extensible, nonlinear elastic dumbbell model to study the viscoelastic effect of dilute polymer solutions. Mohammad (1992) examined the flow behavior of viscoelastic polymer solutions by means of natural and artificial core experiments. He found a critical injection rate, beyond which the "elastic viscosity" of polymer solutions manifests itself in the rise of effective viscosity and corresponding influential parameters including concentration, degree of hydrolyzation, molecular weight, core permeability, salinity and temperature. Wang (1994) got the rheologic curve of polyacrylamide solution through experiment and found that viscoelastic effect of polymer is exhibited only when passing through the porous media and therefore dependent on shear rate. Zhang (2007, 2008) used constricted/expanded channels to model the pore throat in porous media and numerically studied the flow of viscoelastic polymer solution in pore throat model. It is found that smaller throat size leads to greater "elastic viscosity" and higher flow resistance. The micro-swept coefficient rises with the increase of "elastic viscosity". The rheological behavior of polymer solution was modeled with an Ellies-type viscoelastic model by Masuda et al. (1992). The calculated polymer flooding performances were compared well with the experimental data. Based on the lab and field experiments, Wang (2000a, 2000b) found that the increase in micro-scale recovery was related to the elasticity of polymer fluids and HPAM fluids can improve micro-scale displacement efficiency in cores. Xia (2001, 2002, 2004, 2007) further compared capability of different polymers experimentally.

However, there is few combined theoretical and computational analysis in the roles of viscoelasticity involved in polymer flooding, in particular, microscopically. Therefore, we aim at the examination of viscoelastic effects of HPAM solution by simulating chemical flooding of HPAM solution in this article. First, a constitutive equation of the viscoelastic HPAM solution verified by comparison with measurements is established. Then a physical model of 3D viscoelastic polymer flooding is constructed, taking into consideration

various complicated physicochemical phenomena such as convection, dispersion, diffusion, chemical adsorption and rheological behavior of polymer solution and so on. Finally, the effects of major physical parameters on displacement efficiency and corresponding microscopic mechanism are examined in details on the basis of numerical simulation of viscoelastic polymer flooding.

2 Viscoelastic Constitutive Equation of HPAM Solutions

The polymer agents used in chemical flooding such as glycerin, Xanthan gum, glucose, polyacrylamide and so on exhibit different elasticity behaviors. For instance, micro-scale experiments indicate that the elastic effects of polyacrylamide solution become larger when flowing through porous media (Littmann 1988).

Why do the polymer solutions have viscoelasticity? Polymer turns out a macromolecular compound composed of identical structural units typically connected by covalent chemical bonds so that its molecular size can reach as large as $0.1\text{--}0.3\ \mu\text{m}$. Therefore, polymers are characteristic of a long, flexible chain and entangled molecular structure. Normally polymer molecules exist in solution in the form of loose, sphere-like coils, as illustrated in Fig. 1. As they are flowing through a pore large enough, the frizzy polymer molecules would not be strained and then the apparent (or effective) viscosity is identical to shear viscosity alone. However, the pore channel in the natural reservoir usually is tortuous and converging/diverging, which results in alternative acceleration and deceleration of the fluid in the porous media. Consequently, polymer solutions entering a converging section are subjected to not only shear, but also stretch or elongation in the direction of flow. At this moment, the flow behavior of polymer solutions can be explained by two distinct processes: shear flow and strain flow. The deformation of polymer molecules may result in an increase in effective viscosity. Due to the increased viscosity is caused by the elastic response of polymer molecules, namely, elastic viscosity or viscosity due to elasticity simplified as “viscoelasticity” in this article is used to indicate the effect of elasticity of polymer solution on the growth of effective viscosity.

Experiments are performed to observe the rheological properties of polymer solution (Mohammad 1992; Wang 1994). Figure 2 depicts the rheology of polyacrylamide solution. The dashed line indicates the shear viscosity measured with viscometer, while the solid line is the apparent viscosity measured when the polymer solution flows in porous media cores, which can be divided into three regions. In Zone 1, there is no stretching strain when polymer solutions pass through the porous media under low shear rate. Newtonian behavior is

Fig. 1 Typical flow schematic diagram of macromolecular polymer solution in porous media

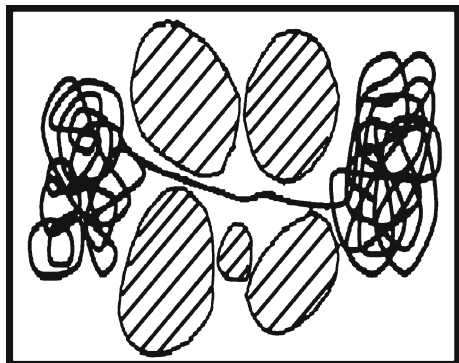
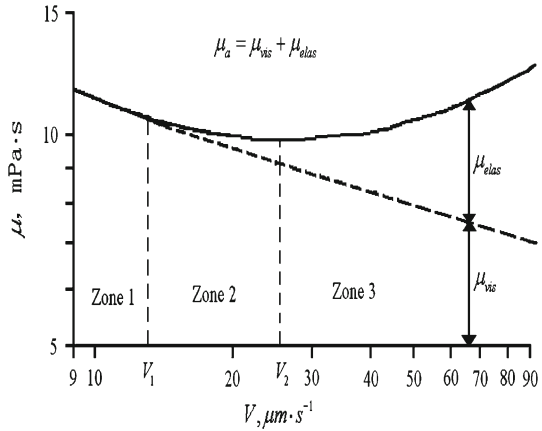


Fig. 2 Rheological characteristic curve of HPAM solution (solid dash line is apparent viscosity, dashed line is viscous viscosity, the viscosity difference is considered as “elastic viscosity”)



exhibited. So the apparent viscosity is equal to shear viscosity. With the increase of flow velocity, the viscosity measured with viscometer (shear viscosity) is smaller than the viscosity measured when the polymer solution flows in porous media cores (effective viscosity). Such a viscosity difference is obviously due to the elastic effect of polymer solution. So we call this kind of viscosity difference as viscosity due to elasticity. In Zone 2, a pseudoplastic rheology is found, namely, shear viscosity decreases with shear rate. In Zone 3, the elongational flow has a dominant position during the seepage flow process. The “elastic viscosity” has an obviously effect on apparent viscosity. A dilatant rheology is used to describe the behavior of polymer solution. The apparent viscosity increases with the shear acceleration.

When the polymer solutions flow through the porous media, shear flow and elongational flow coexist. The apparent viscosity of polymer solution μ_a consists of shear viscosity μ_{vis} and elastic viscosity μ_{elas} . Then, we have

$$\mu_a = \mu_{vis} + \mu_{elas} \tag{1}$$

where the shear viscosity for a non-Newtonian solution can be written as a function of shear rate $\dot{\gamma}$ as below (Wang 1990):

$$\mu_{vis} = \mu_w \left(1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{min}} \right)^{n-1} (A_{p1} C_{ap} + A_{p2} C_{ap}^2 + A_{p3} C_{ap}^3) \right) \tag{2}$$

where μ_w is the viscosity of water, $\dot{\gamma}_{min}$ is the minimum shear rate within the range of pseudoplastic fluid, C_{aap} is the polymer concentration; A_{p1}, A_{p2}, A_{p3} are constants. In the meantime, elastic viscosity can be derived by the following procedures: Mashall and Metzner (1967) had given a definition of relaxation time θ_f . It can be seen as the ratio of the magnitude of the elastic force to that of the shear force

$$\theta_f = \frac{\sigma_{11} - \sigma_{22}}{2\dot{\gamma}\tau} \tag{3}$$

in which normal stress difference, $\sigma_{11} - \sigma_{22}$, represents elastic force.

$$\sigma_{11} - \sigma_{22} = -\mu_{elas}\dot{\epsilon} \tag{4}$$

The relationship between shear stress τ and shear rate $\dot{\gamma}$ is:

$$\tau = -\mu_{vis}\dot{\gamma} \tag{5}$$

Substitution of Eqs. 4 and 5 into Eq. 3 yields

$$\frac{\mu_{\text{elas}}}{\mu_{\text{vis}}} = \frac{2\theta_f \dot{\gamma}^2}{\dot{\epsilon}}, \tag{6}$$

The stretching rate $\dot{\epsilon}$ can be expressed as:

$$\dot{\epsilon} = \frac{1}{l_0} \frac{dl}{dt}, \tag{7}$$

and l_0 is equal to the particle diameter of the reservoir, D_p . $\frac{dl}{dt}$ represents the actual flowing velocity, v_ϕ , of fluid in the porous media. Darcy velocity v_d is used mostly in seepage field. The relationship between actual velocity and Darcy velocity is

$$v_\phi = v_d \sqrt{T} / \phi, \tag{8}$$

T is the tortuosity ranging from 25/12 to 2.5 and ϕ is porosity.

Putting Eqs. 7 and 8 in Eq. 6, one arrives at an equation:

$$\frac{\mu_{\text{elas}}}{\mu_{\text{vis}}} = \frac{2\theta_f D_p \phi \dot{\gamma}^2}{v_d \sqrt{T}}, \tag{9}$$

So, the viscosity of polymer solution in porous media looks like:

$$\mu_a = \mu_{\text{vis}} \left(1 + \frac{2\theta_f D_p \phi \dot{\gamma}^2}{v_d \sqrt{T}} \right). \tag{10}$$

From which we see that the augment in viscosity due to elasticity is proportional to relaxation time, particle diameter, porosity and inversely proportional to the Darcy velocity and square root of tortuosity.

In this way, a constitutive equation for HPAM solutions is thus established based on the previous studies.

3 Viscoelastic Polymer Flooding Model

We regard the polymer flooding as an immiscible two-phase flow of oleic and aqueous phases. The aqueous phase consists of soluble polymer and mobile water. Thus, we can disregard the mass transfer between the oleic and aqueous phases. There are a great many complicated physical and chemical processes occurring during polymer flooding. For the sake of simplicity, we assume:

- (1) Both fluids and the reservoir are compressible;
- (2) Generalized Darcy law is applicable to multiphase flow and gravity is taken into account;
- (3) Generalized Fick law is applicable to multicomponent dispersion;
- (4) The permeability reduction of aqueous phase owing to polymer adsorption is considered while the permeability of oleic phase is not affected by polymer solution;
- (5) The flow is isothermal and the reservoir is homogeneous;
- (6) The concentration of injected polymer solution is kept constant.

Therefore, the governing equations based on a quarter of a five-spot well pattern are as follows.

The mass conservation of the oleic phase is:

$$\frac{\partial(\phi s_o \rho_o)}{\partial t} = \nabla \cdot \left(\frac{\rho_o}{\mu_o} k_o \nabla(p_o + \rho_o g Z) \right) + q_o. \tag{11}$$

The mass conservation of the aqueous phase is given by:

$$\frac{\partial(\phi s_a \rho_a)}{\partial t} = \nabla \cdot \left(\frac{\rho_a}{\mu_a} k_a \nabla(p_a + \rho_a g Z) \right) + q_a. \tag{12}$$

The equation of polymer transport is written as:

$$\begin{aligned} & \frac{\partial(\phi s_a \rho_a C_{ap})}{\partial t} + \frac{\partial(\rho_r(1 - \phi)\rho_a \hat{C}_{ad})}{\partial t} \\ & = \nabla \cdot (D\phi s_a \nabla(C_{ap}\rho_a)) + \nabla \cdot \left(C_{ap} \frac{\rho_a k_a}{\mu_a} \nabla(p_a + \rho_a g Z) \right) + q_a C_{awp}. \end{aligned} \tag{13}$$

where ρ, k, μ, p, s is the density, the effective permeability, the viscosity, the pressure and saturation; subscripts o and a represent oleic and aqueous phases, respectively. C_{ap} is the polymer concentration in aqueous phase, g is the gravitational acceleration, \hat{C}_{ad} is the amount of polymer adsorbed per unit mass of rock, C_{apw} is the polymer concentration in the injection well, Z is the depth of reservoir, D is the dispersion coefficient, ρ_r is the density of rock, and q is the source or sink term.

Evidently, the saturation relation is:

$$S_o + S_a = 1. \tag{14}$$

The capillary force equation can be expressed as:

$$p_c = p_o - p_a = \sigma \cos \theta \sqrt{\phi/K} J(s_a). \tag{15}$$

in which p_c is the capillary force, K is the absolute permeability, σ, θ the interfacial tension and the contact angle between the aqueous and oleic phases. $J(s_w)$ is the capillary force function.

The state equations are:

$$\rho_o = \rho_{o0}(1 + C_o(p_o + \rho_o g Z - p_{o0})), \tag{16}$$

$$\rho_a = \rho_{a0}(1 + C_a(p_a + \rho_a g Z - p_{a0})), \tag{17}$$

$$\phi = \phi_0 \left(1 + C_\phi \left(\frac{p_a + p_o + \rho_o g Z + \rho_a g Z}{2} - \frac{p_{a0} + p_{o0}}{2} \right) \right). \tag{18}$$

where C_o, C_a, C_ϕ mean the compressibility of oil, water, and rock, respectively. Subscript 0 indicates physical quantities at a certain condition.

The previous governing equation system is to be solved with initial conditions:

$$p_o(x, y, z, 0) = p_{oi}, S_o(x, y, z, 0) = S_{oi}, C_{ap}(x, y, z, 0) = C_{api}. \tag{19}$$

In which p_{oi}, S_{oi}, C_{api} represent the initial oil pressure, the initial oil saturation, and the initial polymer concentration, respectively.

The boundary conditions:

$$\rho_o v_{on} = -\frac{\rho_o}{\mu_o} k_o \nabla(p_o + \rho_o g Z) = 0, \quad \rho_a v_{an} = -\frac{\rho_a}{\mu_a} k_a \nabla(p_a + \rho_a g Z) = 0. \tag{20}$$

Due to the addition of the polymer, the behaviors of the aqueous phase, including viscosity, permeability, adsorption, etc., have been changed. Therefore, some additional equations must be considered in the polymer flooding model.

3.1 Permeability reduction factor

In water flooding, since the viscosity of water is far less than that of oil, water is easy to penetrate when displacing the oil along the porous channel. This phenomenon is called viscous fingering, which leads to a poor recovery of oil. With the adding of polymer, viscous fingering phenomenon can be avoided or mitigated effectively. Because polymer can reduce the permeability of the aqueous phase, but has no effect on the permeability of the oleic phase. So the sweep efficiency is improved. The permeability reduction factor representing the effect of polymer on the permeability of aqueous phase is defined as $R_k = k_w/k_a$.

And it can be further expressed as (Islam and Farouq 1989):

$$R_k = 1 + (R_{k \max} - 1) \frac{\hat{C}_{ad}}{\hat{C}_{ad \max}}, \tag{21}$$

where $R_{k \max}$ is the maximum permeability reduction factor and $\hat{C}_{ad \max}$ is the maximum adsorption amount per unit mass of rock. Equation 21 implies that the adsorption of polymer leads to the growth of permeability reduction factor.

3.2 Polymer adsorption

There are two mechanisms of polymer adsorption: physical adsorption of the polymer molecule on the surface of the porous media and mechanical entrapment of the polymer within narrow pores of porous media (Baijal 1982). In general, the degree of adsorption of polymer molecules on the surface of rock depends on the nature of polymer molecules and the surface. It is confirmed that the higher the polymer concentration, the higher the degree of adsorption. We use the Langmuir adsorption isotherm to describe the adsorption of polymer as.

$$\frac{\hat{C}_{ad}}{\hat{C}_{ad \max}} = \frac{bC_{ap}}{1 + bC_{ap}}, \tag{22}$$

where b is the adsorption constant.

3.3 Shear rate

The polymer solution is a non-Newtonian fluid. It is a well-known fact that the usual power law formulation may be employed for depicting the properties of non-Newtonian fluid (Wang 1990). Therefore, a suitable expression is needed to calculate the value of shear rate, which is applicable to the flow conditions of polymer solutions through porous media. The shear rate considering the permeability reduction effect, connectivity of channel pore and tortuosity is described by the following expression:

$$\dot{\gamma} = \left(\frac{3n + 1}{4n} \right)^{\frac{n}{n-1}} \frac{v_a}{\sqrt{0.5TKk_{rw}\phi s_w/R_k}}, \tag{23}$$

in which n is the shear rate exponent, v_a is the percolation velocity of the aqueous phase, and k_{rw} is the relative permeability to water.

3.4 Viscosity of Viscoelastic Polymer Solution

When polymer solutions flow through porous media, polymer molecules are distorted by the flow through tortuous and converging or diverging pore channels. The curly molecules need

enough time to relax and change their configurations, so the polymer solution will show an elastic response in addition to the viscous one. Especially in high-shear-rate regions, such as the vicinity of injectors and producers, the “elastic viscosity” cannot be neglected.

Substitution of expression of shear viscosity Eq. 2 and shear rate Eq. 23 into Eq. (10) yields the apparent viscosity of polymer solution

$$\mu_a = \mu_w \left(1 + \left(\frac{\dot{\gamma}}{\dot{\gamma}_{\min}} \right)^{n-1} \left(A_{p1} C_{ap} + A_{p2} C_{ap}^2 + A_{p3} C_{ap}^3 \right) \right) \left(1 + \left(\frac{3n+1}{4n} \right)^{\frac{2n}{n-1}} \frac{4\theta_r D_p R_k}{T^{3/2} K k_{rw} S_w} v_a \right). \tag{24}$$

4 Model Verification and Validation

In order to verify the constitutive relationship established, we have compared the theoretical formula with viscosity measurement. At the same time, the simulated results based on FDM algorithm when numerically solving foregoing equation system are compared with the experimental coring data in the laboratory to validate the present physical model.

Xia (2002a) used viscometers to characterize the rheological properties of polymer solutions when experimentally examining the “elastic viscosity” of polymer solutions in detail. Based on the constitutive equation established, we have also obtained calculated viscosity as HPAM solutions pass through the cores. The agreement between calculation and experiment is satisfactory as shown in Fig. 3.

In order to further display the role of the elasticity of HPAM solutions, liquids were injected into cores in two kinds of flooding sequence: water → glycerin → HPAM and water → HPAM → glycerin. The coincident results between calculation and core data are satisfactorily shown in Fig. 4a and b, respectively. It can be seen that with water flooding in advance, whether glycerin or HPAM is injected first, the recovery is enhanced. This is because both glycerin and HPAM may ultimately lead to the growth in the viscosity of polymer solution and thus the macroscopic sweep volume as well. Two additional phenomena are observed

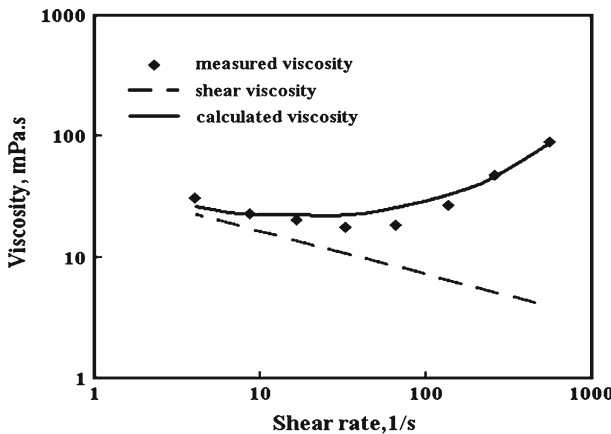


Fig. 3 Comparison between the experimental and calculated viscosities (solid line is calculated results, broken line is shear viscosity, dot is experimental results)

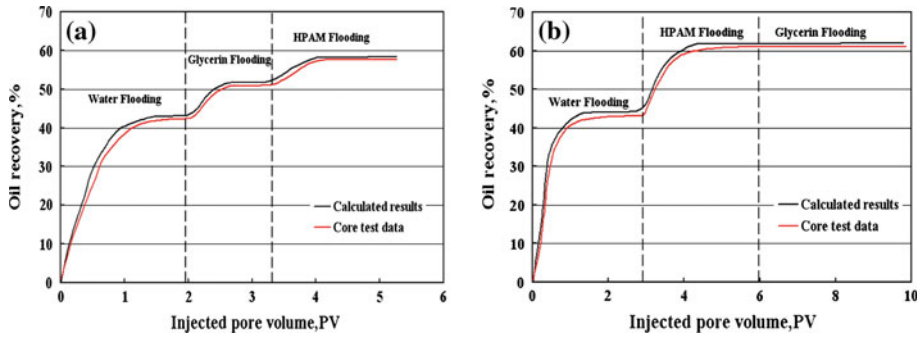


Fig. 4 Comparison between the core test and calculated oil recoveries (*black line* is calculated results, *red line* is core test data): **a** flooding sequence is water → glycerin → HPAM; **b** flooding sequence is water → HPAM → glycerin

from Fig. 4a and b: (1) the incremental recovery is larger as expected if HPAM is injected first. For example, the incremental recovery is about 8.5% OOIP (original oil in place) for glycerin in Fig. 4a, while it is 17.7% OOIP for HPAM in Fig. 4b. (2) We find that when HPMA flooding may amplify the effect of glycerin in Fig. 4a by 6.5% OOIP, glycerin flooding is of no use in this regard in Fig. 4b. The larger elasto-viscosity of HPMA is responsible for above-mentioned phenomena implied in Fig. 4.

Our simulated results can also be quantitatively confirmed by Xia et al. (2002b, 2008) who studied the oil displacement efficiencies of viscoelastic HPAM solution and viscous glycerin solution by flooding at visual microscopic glass models. The comparison between them is shown in Table 1. Although microscopic oil displacement experiments indicate that the displacement efficiencies of both HPAM and glycerin solution flooding gradually increase with viscosity, the former is always higher than the latter at the same viscosity, capillary number and oil saturation. Our calculation comes to the same conclusion.

Table 1 Physical parameters in simulation

Physical parameter	Value	Physical parameter	Value
Length, l (m)	140	Water viscosity, μ_w (Pa.s)	10–3
Width, w (m)	140	Oil viscosity, μ_o (Pa.s)	5E–3
Thickness, h (m)	10	Rock density, ρ_r (kg/m ³)	2.5E+3
Porosity ϕ_0	0.25	Tortuosity, T	1.5
Initial oil density, ρ_{o0} (kg/m ³)	800	Shear rate exponent, n	0.68
Initial water density, ρ_{w0} (kg/m ³)	1000	Langmuir adsorption constant, b	0.12
Compressibility coefficient of oil, C_o (Pa ⁻¹)	8E–10	Maximum adsorption amount per unit mass of rock, $\hat{C}_{ad\ max}$ (kg/kg)	3E–6
Compressibility coefficient of water, C_w (Pa ⁻¹)	5E–10	Bottom pressure of the production well, p_{wf} (Pa)	10E+6
Compressibility coefficient of rock, C_ϕ (Pa ⁻¹)	6E–10	Maximum permeability reduction factor, $R_{k\ max}$	1.5
Interfacial tension, σ (N m)	2.5E–2	Well radius, r_{eo} (m)	0.1
Initial oil pressure, p_{oi} (Pa)	12E+6	Relaxation time, θ_r (s)	0.0015
Initial oil saturation, S_{oi}	0.855	Concentration of HPAM, C_{ap} (ppm)	1000

5 Results and Discussion

In this section, the polymer flooding model is used to simulate the flow behavior of polymer solutions in porous media. As case studies for a given reservoir, the physical variables are listed in Table 2. The simulations were performed on a 1/4 of a five-spot pattern. The distance between the injection well and the production well is about 200m. The concentration of injected HPAM solutions is 1000 ppm.

In Fig. 5, the evolution of the aqueous pressure as functions of time and space is demonstrated. Generally speaking, the initial injection pressure always is very high. The pressure of production well is lower than the pressure of injection well. The pressure drop between two kinds of wells is the right force to drive the oil out. In chemical flooding, the injected polymer solutions improve the viscosity of aqueous phase and correspondingly raise the flow resistance of displacement fluid. As a result, higher injected pressure is required to displace polymer resolution. With the exploitation process going on, the pressure drop near the production well spreads around and the surrounding pressure is gradually decreasing.

Figure 6 shows the spatial and temporal evolution of the concentration of HPAM when 1000ppm HPAM solution is injected into the reservoir. On the horizontal axis, the origin and the point of $x = 200$ m represent the location of injection wells and production well, respectively. Initially, the concentration of HPAM is zero throughout the reservoir except for the injection well. Since polymer solution is injected continuously, the concentration of HPAM at the injection well always maintain 1000ppm. With the migration of injected solution from injection well to production well, the concentration of HPAM nearby the injection well is gradually increasing. The concentration profiles intuitively reflect the tempo-spatial evolution of HPAM concentration of HPAM. Black, red and purple lines show the spatial distribution of concentration from the injection well to production well when 2.2, 4.5 and 6.5 PV HPAM solutions are injected into the reservoir, respectively. The temporal evolution of concentration of HPAM can be shown by observing the change of concentration value somewhere in the reservoir, such as $x = 100$ m. The concentration of HPAM is about 350ppm when the injected HPAM solutions are 2.2 PV. With the displacement progress, the concentration of HPAM is gradually increasing.

Figures 7, 8, and 9, respectively, show the effect of polymer concentration, reduction factor of maximal permeability, and relaxation time on the oil recovery.

Polymer, as a chemical reagent, is added into the water to improve the mobility ratio between the aqueous phase and oleic phase. Its concentration obviously plays an

Table 2 Comparison of displacement efficiency between the experimental and calculated results

C_{ap} (ppm)	HPAM flooding					Glycerin flooding				
	μ_a (mPa s)	Experimental results		Calculated results		μ_a (mPa s)	Experimental results		Calculated results	
		E (%)	ΔE (%)	E (%)	ΔE (%)		E (%)	ΔE (%)	E (%)	ΔE (%)
H ₂ O	1.0	25.50	0	24.92	0	1.0	25.46	0	25.18	0
500	29.3	32.26	4.76	29.44	4.52	13.0	33.24	7.78	32.76	7.58
1000	65.4	41.77	16.27	41.00	16.08	34.2	33.46	8.0	32.98	7.80
1500	111.0	51.78	26.28	50.86	25.94	57.0	34.09	8.63	33.73	8.55

E displacement efficiency, ΔE increment of E , compared with water flooding

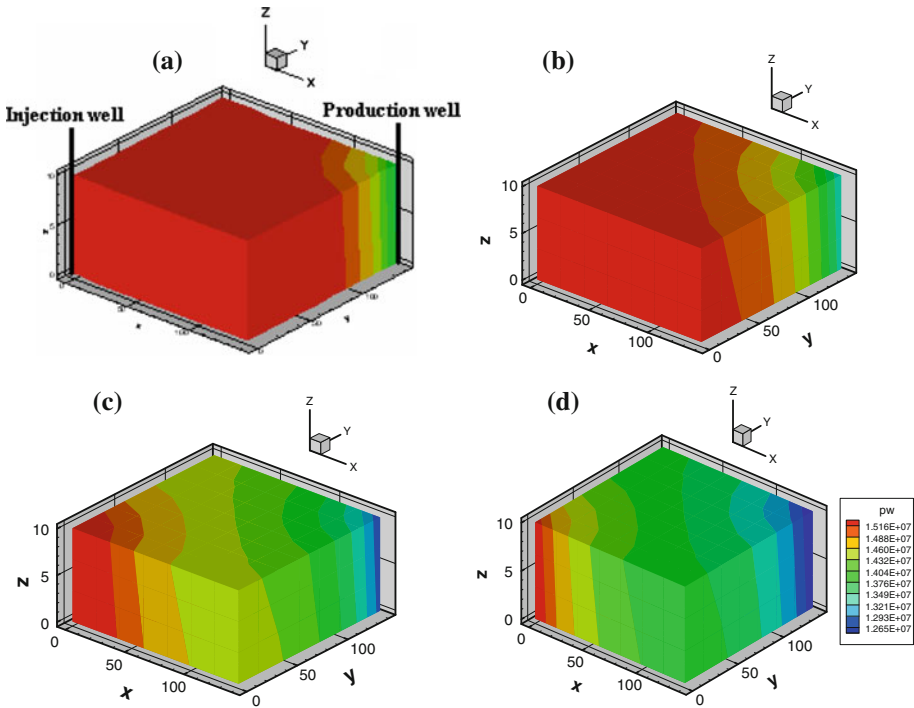


Fig. 5 Aqueous pressures over time and space: **a** time=0.74 PV; **b** time=1.62 PV; **c** time=3.23 PV; **d** time=6.52 PV

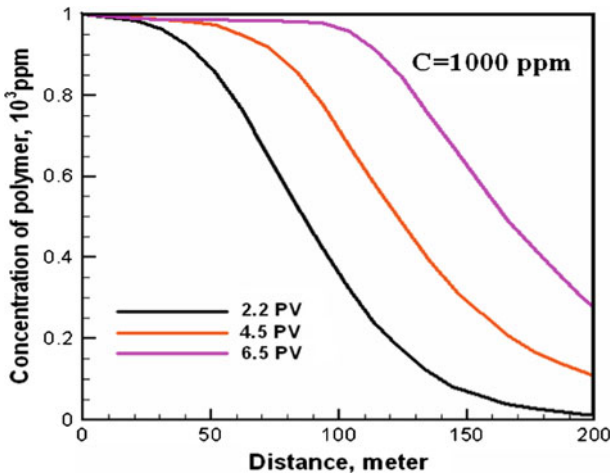


Fig. 6 Concentration profiles of HPAM (black, red and purple lines represent time=2.2 PV, 4.5 PV, and 6.5 PV respectively)

important role on the displacement efficiency. Figure 7 shows oil recovery increase with polymer concentration, namely, higher HPMA concentration means larger capabilities of mitigating viscous fingering and driving efficiency and thus leads higher oil recovery.

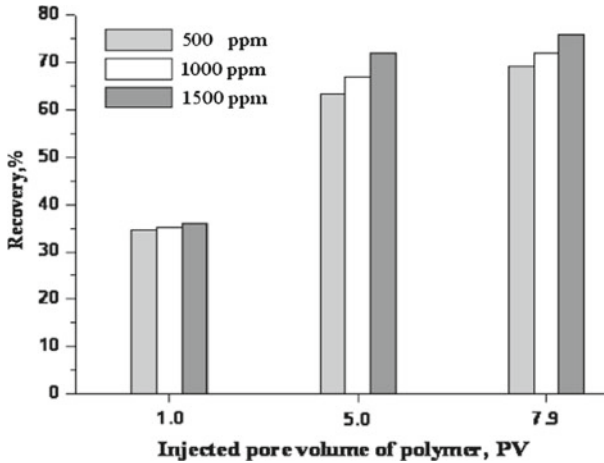


Fig. 7 The effect of HPAM concentration on recovery

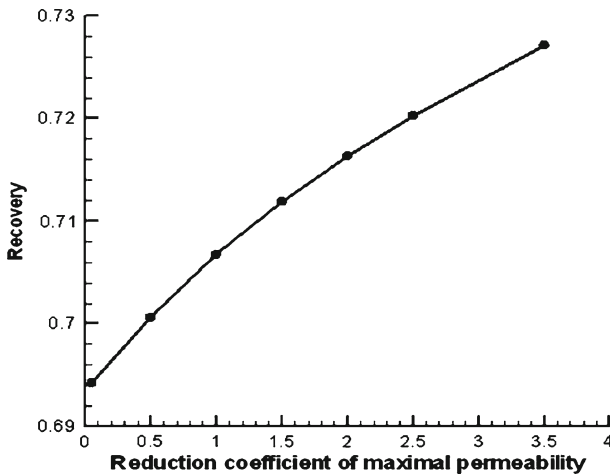


Fig. 8 The effect of reduction coefficient of maximal permeability on recovery

From Fig. 8, it can be seen that the oil recovery increase with the increase of reduction factor of maximal permeability. The common views think that the addition of polymer can reduce the permeability of the aqueous phase and inhibit the viscous fingering phenomenon. So the displacement fluid can improve the micro sweep efficiency. Higher the reduction factor of maximal permeability, higher the oil recovery.

As shown in Fig. 9, the longer the relaxation time, the higher the oil recovery. Longer relaxation time means that the polymer molecules spend longer time to adjust their structure, implying the effect of elasticity is more prominent. And more residual oil can be brought out from the reservoir. So when we select the polymer, we prefer to use those with longer relaxation time. The water-soluble polymer, used to enhance oil recovery, can be divided into two categories: synthetic polymers, produced by synthetic method, and polysaccharides, coming from natural materials such as wood, seeds or produced by bacteria or fungi. Polyacrylamide is one of the synthetic polymers. And Xanthan gum is a typical polysaccharide. Zhang et al.

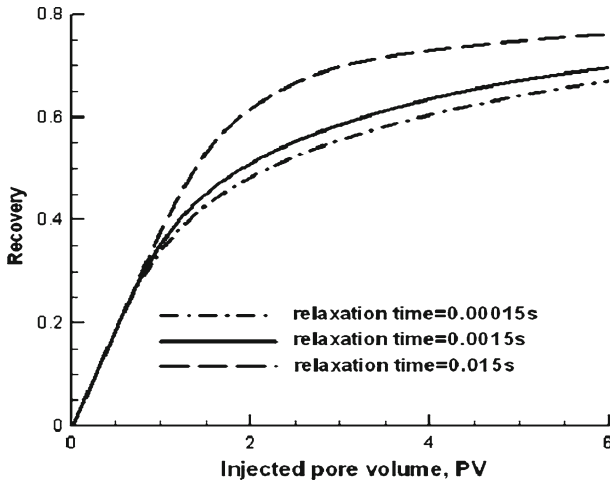


Fig. 9 The effect of relaxation time on recovery

(2009) examined the rheological behavior of HPAM solutions and Xanthan gum in porous media experimentally. Displacement experiments were conducted with various concentrations and injecting speeds. It was found that the increase of apparent viscosity generated by the entanglement of polymer molecules can increase the force parallel to oil–water interface and enhance oil recovery. With the concentration increase of HPAM solutions, the apparent viscosity increases correspondingly. Nevertheless, when the concentration of Xanthan solutions was higher than the entanglement concentration, the apparent viscosities varied little. Xanthan gum molecules have clubbed structure and its rigidity is larger. The flexible polyacrylamide molecules have curly shape. So the elastic effect of Xanthan gum is much smaller than that of polyacrylamide. Therefore, the difference in molecular structure of the two kinds of polymers is the right mechanism responsible for the experimental results.

Figure 10 shows the variation of injection pressure with relaxation time. If the relaxation time is smaller, which corresponds to the situation without elasticity, the injection pressure is the smallest. With the increasing of relaxation time, the pressure of injection well increases a well. As you know, when the curled, spherical polymers molecules pass through the throat of pores, it takes some time to elongate by adjusting its molecular structure. The longer relaxation time means stronger elasticity of polymer molecules. Moreover, Gogarty et al. (1972) indicated that elastic fluids are subjected to a process of expansion and contraction as entering and leaving a pore. Consequently, the overall pressure drop across a core for viscoelastic fluids should be greater than that for pure viscous fluids, which means an additional pressure drop is necessary to drive viscoelastic fluids.

It is obviously seen in Fig. 11 that the oil recovery of viscoelastic HPAM is higher than that of pure viscous glycerin. With water flooding applied, the residual oil mainly remain at the places where water has not swept through, such as oil film on the rock surface, oil in “dead end” or pores throat. Residual oil in “dead ends” is immovable mainly because of constrained rock configuration. The residual oil trapped in pore throat by capillary forces appears in the form of droplet. Nevertheless, viscoelastic polymer with long molecular chains can tangle up and pull out molecular chains to haul residual oil both behind and beside it. The experimental results have shown the amount of residual oil pulled out of the “dead ends” is indeed proportional to the elasticity of the polymer solutions. As for part of residual oil

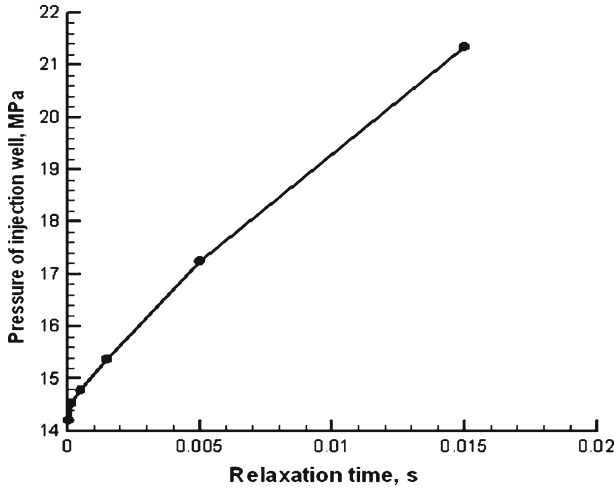


Fig. 10 Injection well pressure versus relation time

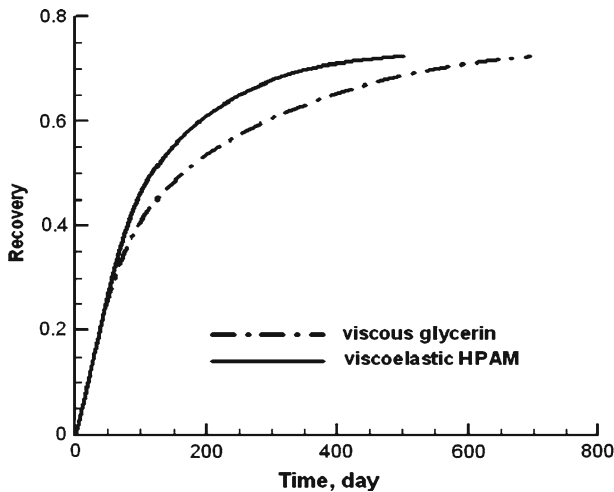


Fig. 11 Comparison of recovery between viscous glycerin flood and viscoelastic HPAM flood (*dash dot line* is viscous glycerin; *solid line* is viscoelastic HPAM)

adsorbed on the rock surface, they can also be driven out due to larger velocity gradient at the rock surface for elastic polymer by getting rid of oil film from rock surface. In a word, the oil displacement efficiency for elastic polymer can be remarkably enhanced in many ways so that EOR of 5% can be attributed to the role of polymer elasticity.

6 Conclusions

- (1) Among polymers, HPAM solutions with long, curly chain structure are found to possess elastic response when they pass through the porous media. The additional viscosity is

- proportional to particle diameter, relaxation time of polymers, and inversely proportional to the Darcy velocity and square root of tortuosity of porous media.
- (2) The EOR mechanism of viscoelastic polymer flooding is twofold. On the one hand, additional viscosity further prohibits viscous fingering so that volumetric sweeping is expanded macroscopically. At the same time, the oil displacement efficiency is enhanced due to the deformation of long-chained molecular structure microscopically so that the residual oil can be hauled out in dead ends or pore throats and on the rock surface. The amount of EOR can be around a few percent and the oil actually can be exploited out earlier.
 - (3) Compared with the viscous polymer solutions, the required injection pressure of viscoelastic polymer flooding is higher. Hence, the injection of displacement fluid becomes more difficult with the increasing of elastic effect. This is a challenging issue in chemical flooding technique.
 - (4) Relaxation time is a characteristic parameter representing the elastic behavior of the polymers and plays a decisive role in selecting viscoelastic polymer for chemical flooding. We know that the longer the relaxation time, the higher the oil recovery. On the other hand, the injection pressures increase with relaxation time. We need to have an overall consideration technically and economically in this regard.

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References

- Acharya, A.: Particle transport in viscous and viscoelastic fracturing fluid. *SPE Prod. Eng.* **1**(2), 104–110 (1986)
- Baijal, S.K.: *Flow Behavior of Polymers in Porous Media*. PennWell Publishing Company, Tulsa (1982)
- Bird, R., Armstrong, R., Hassager, O.: *Dynamics of Polymeric Liquids*. Wiley, New York (1987)
- Gogarty, W., Levy, G., Fox, V.: Viscoelastic effects in polymer flow through porous media. In: Fall Meeting of the Society of Petroleum Engineers of AIME, pp 1–16. San Antonio (1972)
- Guo, S.: *Physical Chemistry Seepage*. Science Press, Beijing (in Chinese) (1990)
- Han, D.: Recent development of enhanced oil recovery in China. *J. Petrol. Sci. Eng.* **22**(1–3), 181–188 (1999)
- Islam, M., Farouq, S.: New scaling criteria for polymer emulsion and foam flooding experiments. *J. Can. Petrol. Technol.* **28**(4), 79–87 (1989)
- Littmann, W.: *Polymer Flooding*. Elsevier, New York (1988)
- Marrucci, G.: Limiting concepts in extensional flow. *Polym. Eng. Sci.* **15**(3), 229–233 (1975)
- Marshall, R., Metzner, A.: Flow of viscoelastic fluids through porous media. *Ind. Eng. Chem. Fundam.* **6**(3), 393–400 (1967)
- Masuda, Y., Tang, K., Miyazawa, M.: 1D simulation of polymer flooding including the viscoelastic effect of polymer solution. *SPE Res. Eng.* **7**(2), 247–252 (1992)
- Mohammad: Quantification and optimization of viscoelastic effects of polymer solutions for enhanced oil recovery. In: Proceedings of the SPE/DOE 8th symposium on EOR, SPE 24154, pp. 22–24. Tulsa, 22–24 April 1992
- Shen, P.: *The Theory and Experiment of Water and Oil Flow in Porous Media*. Oil Industry Press, Beijing (in Chinese) (2000)
- Smith, F.: Behavior of partially hydrolyzed polyacrylamide solutions in porous media. *J. Pet. Tech.* **22**(2), 148–156 (1970)
- Wang, X.: Determination of the main parameters in the numerical simulation of polymer flooding. *Petrol Explor. Develop.* **17**(3), 69–76 (in Chinese) (1990)
- Wang, W.: Viscoelasticity and rheological property of polymer solution in porous media. *J. Jiangnan Petrol. Inst.* **16**(4), 54–57 (1994)
- Wang, D., Cheng, J., Yang, Q.: Viscous-elastic polymer can increase microscale displacement efficiency in cores. In: SPE annual technical conference and exhibition, pp. 1–5. Dallas. (2000a)
- Wang, D., Cheng, J., Yang, Q.: The HPAM solution with visco-elastic behavior can increase microscale displacement efficiency in cores. *Acta. Petrol. Sinica.* **21**(3), 45–51 (in Chinese) (2000b)

- Warner, H.: Kinetic theory and rheology of dilute suspensions of finitely extensible dumbbells. *Ind. Eng. Chem. Fundam.* **11**(3), 379–387 (1982)
- Xia, H., Wang, D., Liu, Z.: Study of the mechanism of polymer solution with visco-elastic behavior increasing microscopic oil displacement efficiency. *Acta. Petrol. Sinica.* **22**(4), 60–65 (in Chinese) (2001)
- Xia, H.: *Percolation Theory of Viscoelastic Polymer Solutions and Its Application*. Oil Industry Press, Beijing (in Chinese) (2002)
- Xia, H., Wang, D., Guan, Q.: The experiment of viscoelastic characteristic of polymer solution. *J. Daqing. Petrol. Inst.* **26**(2), 105–108 (in Chinese) (2002a)
- Xia, H., Wang, D., Hou, J.: The effect of viscoelastic characteristic of polymer solution on oil displacement efficiency. *J. Daqing. Petrol. Inst.* **26**(2), 109–111 (in Chinese) (2002b)
- Xia, H., Wang, D., Wu, J.: Elasticity of HPAM solutions increases displacement efficiency under mixed wettability conditions. In: *SPE Asia Pacific Oil and Gas Conference and Exhibition*, pp. 1–8. Perth. (2004)
- Xia, H., Li, D., Ma, W.: Experiments research of polymer solution viscoelasticity. *J. Cent. South. Univ. Technol.* **14**(Suppl.1), 206–209 (2007)
- Xia, H., Wang, D., Wang, G.: Effect of polymer solution viscoelasticity on residual oil. *Pet. Sci. Technol.* **26**(4), 398–412 (2008)
- Zhang, H., Wang, D., Yue, X.: Various types of polymer solution's mechanism of action on residual oil in porous media. *Acta. Polym. Sin.* (6), 520–524 (2009)
- Zhang, L.: Mechanism for viscoelastic polymer solution percolating through porous media. *J. Hydrodyn. Ser. B* **19**(2), 241–248 (2007)
- Zhang, L., Yue, X.: Displacement of polymer solution on residual oil trapped in dead ends. *J. Cent. South. Technol.* **15**(Suppl.1), 84–87 (2008)