Effect of shear thickening property of polymer on relative permeability

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Abstract: The relative permeability at a high Darcy velocity was estimated by combining a numerical simulation model that considers the rheology of polymer in shear thickening region. After verifying the robustness of the method, the effect of shear thickening property of polymer on relative permeability was studied. The results show that when Darcy velocity exceeds 17.61 m/d, the apparent relative viscosity of polymer solution begins to increase, and the rheology of polymer changes from shear thinning to shear thickening behavior, which reduces water relative permeability. For water relative permeability model, as Darcy velocity increases, water relative permeability at residual oil decreases in a power function and exponent of water relative permeability model increases linearly.

1. Introduction
In polymer flooding, the polymer dissolved in water will change the relative flow between oil and water by increasing the aqueous-phase viscosity, which will affect relative permeability [1]. In addition to directly changing polymer viscosity, the change of polymer rheology caused by the change of Darcy velocity in shear thinning region will also affect the relative permeability [2]. Darcy velocity varies greatly for multiphase flow in porous media (e.g., radial flow from near-wellbore to far-field), which causes polymer to exhibit different rheological properties (e.g., shear thinning and shear thickening) [3]. However, the effect of shear thickening properties of polymer on relative permeability has not been studied.

The existing methods for calculating relative permeability are mainly steady-state method and unsteady-state method [4]. The steady-state method, which is difficult to achieve oil-water stable flow, is not suitable for high Darcy velocity in shear thickening region. Because of the limitation of mathematical model, the unsteady-state method fails to directly obtain relative permeability at high Darcy velocity in shear thickening region. Relative permeability at a high Darcy velocity was therefore estimated by combining a numerical simulation model that considers the rheology of polymer in shear thickening region. With that, the effect of shear thickening property of polymer on relative permeability was studied.
2. Estimation Method of Relative Permeability
The relative permeability was estimated by automatically matching actual and predicted production data, in which the actual production data was obtained by coreflooding experiment, the predicted data was obtained by numerical simulation model, and the automatic history matching was performed through an optimization algorithm.

2.1. Characterization of polymer properties in numerical model
Based on the black oil model, a numerical simulation model of oil-water two-phase polymer flooding was established. The mass conservation equation [5] of polymer component is as follows,

$$
\nabla \cdot \left[ \frac{kk_p c_p}{\mu_p B_w} \nabla p_w - \rho_c g \nabla D \right] + \nabla \cdot \left[ d_p \varphi \left( 1 - F_p \right) S_w \nabla c_p \right] + q_w c_p = 0
$$

where, $k$ and $k_{rw}$ refer to absolute and relative permeability respectively; $\mu_p$ is apparent viscosity of polymer; $r_k$ is reduction factor of permeability; $d_p$ is polymer diffusion coefficient; $F_p$ is inaccessible pore volume; $\dot{c}_p$ is adsorbed mass concentration of polymer; $c_p$ is mass concentration of polymer; $\varphi$ is porosity.

As a non-Newtonian fluid, the apparent viscosity of polymer is usually characterized by a power function [6]. Polymer solution tends to show shear-thinning behavior at low and medium shear rates and shear-thickening behavior at high shear rate, which are characterized by different power functions. A representation model of apparent viscosity of polymer in shear-thickening region was established by Galindo-Rosales et al. [7] in log-log plot. As follows,

$$
\log \left( \mu_p \right) = \log \left( \mu_{max} \right) + \frac{\log \left( \mu_{min} \right) - \log \left( \mu_{max} \right)}{1 + \left( K \cdot \log \left( \gamma \right) \right)^m}
$$

where, $\mu_{max}$ is apparent viscosity at maximum shear rate in shear-thickening region; $\mu_{min}$ is apparent viscosity at minimum shear rate in shear-thickening region; $\gamma$ is shear rate; $K$ and $m$ are constants.

A formula is introduced to calculate the shear rate at different Darcy velocity in polymer-flooding numerical simulation model [8].

$$
\gamma = a \cdot \left( \frac{3b + 1}{4b} \right)^{b-1} \frac{v_D}{\sqrt{kk_p \rho_s s_w}}
$$

where, $a$ is a constant with default value of 6; $b$ is a power exponent and its default value is 0.5.

In addition, other physical parameters of polymer, including inaccessible pore volume, residual resistance factor, diffusion and adsorption, are also considered in the numerical model.

2.2. Automatic matching of production data
The optimization algorithm updates relative permeability by changing the parameters of relative permeability model, which makes polymer-flooding numerical model generate new predicted production data. In the iterations, when the latest predicted production data reaches the best match with the production data obtained by coreflooding experiment, the automatic matching of production data stops, and the latest relative permeability in numerical model is the optimal estimated relative permeability.

The relative permeability model is characterized by a power law function [9] as shown in Eq. (4) and (5).

$$
k_{rw}(s_w) = k_{rw}(s_{or}) \left( \frac{s_u - s_{wi}}{1 - s_{or} - s_{wi}} \right)^{n_w}
$$
where, $s_w$ refers to water saturation; $s_{wi}$ refers to irreducible water saturation; $s_{or}$ refers to residual oil saturation; $k_{ro}(s_{or})$ refers to water relative permeability at residual oil; $n_w$ refers to exponent of power-law model of water relative permeability.

$$k_{ro}(s_w) = \left( \frac{1 - s_{or} - s_{wi}}{1 - s_{or} - s_{wi}} \right)^{n_w}$$

(5)

where, $k_{ro}$ refers to oil relative permeability; $n_o$ refers to exponent of power-law model of oil relative permeability.

By observing Eq. (4) and (5), it is found that water relative permeability model is controlled by water relative permeability at residual oil and exponent, and oil relative permeability model only limited by exponent. The relative permeability can be changed by adjusting these model parameters. In order to realize the optimal matching between actual and predicted production data faster and more accurately, Levenberg-Marquardt method is applied to perform automatic matching. Since coreflood is carried out at a constant rate, only cumulative oil production along with injection pressure are regarded as actual production data.

### 2.3. Verification of estimation method of relative permeability

A numerical simulation model of polymer flooding with predefined relative permeability replaces coreflooding experiment to provide actual production data, and the predefined relative permeability is therefore regarded as actual relative permeability. The numerical model providing predicted production data is input into a set of random relative permeability curve (grey curve in Fig. 2) at the beginning of automatic matching. As long as the relative permeability estimated by the proposed method matches well with the predefined one, it means that the method is robust. It is noted that the square section with equal area is used to represent the circular section of core in numerical model. In addition, the core and fluid parameters of the numerical model are all measured by experiments (see Table 1 and Fig.1).

| Parameter                          | Value | Parameter      | Value |
|------------------------------------|-------|----------------|-------|
| Polymer concentration, kg/m$^3$    | 1.8   | $\mu_{max}$, mPa·s | 21.8  |
| Injection rate, ml/min             | 6.5   | $K$            | 0.277 |
| TDS of brine, mg/L                 | 10500 | $m$            | 53.2  |
| Brine permeability, ×10$^3$μm$^2$  | 750   | $d_p$,×10$^4$m$^2$/s | 7.3   |
| Viscosity of brine, mPa·s          | 0.78  | $\varphi$, %   | 19.55 |
| Viscosity of oil, mPa·s            | 42.5  | $r_k$          | 3.05  |

The average error of relative permeability curve ($\eta$) is defined to represent the error between the estimated and actual relative permeability curve, which is written as,

$$\eta = \frac{\sum_{i=1}^{n}[k_{atl,i} - k_{atl,i}]}{\sum_{i=1}^{n}k_{atl,i}}$$

(6)

where, $k_{atl}$ refers to actual relative permeability; $i$ refers to point $i$ on relative permeability curve.

Looking at Fig. 2, we can find that the random relative permeability curves at the beginning of automatic matching are significantly away from the actual ones, but the estimated relative permeability curves match the actual ones quite well. The average error of oil relative permeability curve is 3.5%, and the average error of water relative permeability curve is 4.1%, which means the robustness of the estimation method of relative permeability of polymer flooding is good.
3. Effect of shear thickening property of polymer on relative permeability

3.1. Determination of shear thickening region

Apparent relative viscosity ($\mu_{rp}$) was introduced to describe the rheology of polymers flowing in porous media [10], and its expression is as follows,

$$\mu_{rp} = \frac{F_r}{F_{rr}}$$  \hspace{1cm} (7)

where, $F_r$ refers to resistance factor; $F_{rr}$ refers to residual resistance factor.

The polymer solution with concentration of 1.8 kg/m$^3$ flowed through the core at different Darcy velocities (ratio of injection rate to core cross-sectional area), and the apparent relative viscosity was measured according to Eq. (7). As shown in Figure 3, the critical Darcy velocity of shear thinning region and shear thickening region is 17.61 m/d, and the corresponding critical injection rate is 6 ml/min.
3.2. Relative permeability under the influence of shear thickening

6 coreflooding experiments were completed (see Table 2), of which case 1 for comparison was water flooding experiment, and the other 5 experiments were polymer flooding experiments in the shear thickening region (i.e., injection rate from 6 ml/min to 10 ml/min). The relative permeability curves at different injection rates were then estimated by the proposed method.

As shown in Fig. 4, the Darcy velocity in shear thickening region mainly affects water relative permeability, and all water relative permeability curves of polymer flooding are lower than that of water flooding. Further observation shows that water relative permeability decreases with the increase of Darcy velocity. This is because apparent relative viscosity of polymer increases as Darcy velocity increases in shear thickening region (see Fig. 3). By studying water relative permeability models at different Darcy velocities in shear thickening region, it can be found water relative permeability at residual oil endpoint decreases in a power function as Darcy velocity increases (see Fig. 5(a)), and exponent of water relative permeability model increases in a linear function as Darcy velocity increases (see Fig. 5(b)).

![Fig. 3 Rheology of polymer flowing in core](image1.png)

![Fig. 4 Relative permeability curve](image2.png)

| Case | $k$, $10^{-3}$ μm$^2$ | $\phi$, % | Injection rate, ml/min | Darcy velocity, m/d | Residual resistance factor | $s_{wi}$ | $s_{or}$ |
|------|-----------------|--------|------------------------|---------------------|--------------------------|--------|--------|
| 1    | 721             | 19.23  | 6                      | 17.61               | -                        | 0.216  | 0.221  |
| 2    | 686             | 18.65  | 6                      | 17.61               | 3.05                     | 0.211  | 0.215  |
| 3    | 755             | 19.77  | 7                      | 20.55               | 3.01                     | 0.226  | 0.205  |
| 4    | 673             | 18.96  | 8                      | 23.48               | 3.19                     | 0.209  | 0.195  |
| 5    | 666             | 19.33  | 9                      | 26.42               | 3.63                     | 0.213  | 0.198  |
| 6    | 712             | 19.11  | 10                     | 29.35               | 3.96                     | 0.216  | 0.197  |

4. Conclusion

Based on the study of varieties of relative permeability curves under different Darcy velocities in shear thickening region, the key conclusions are as below,

1) The robustness of the proposed relative permeability estimation method is proved by good matching between actual and estimated relative permeability.

2) The critical Darcy velocity of shear thinning region and shear thickening region is 17.61 m/d in this work.
(3) For water relative permeability model, as Darcy velocity increases, water relative permeability at residual oil decreases in a power function and exponent of water relative permeability model increases linearly.

![Graph](image)

(a) Water relative permeability at residual oil endpoint  (b) Exponent of power-law model

**Fig. 5 Effect of Darcy velocity on water relative permeability model**

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