Research on Working Viscosity and Influencing Factors of Polymer Solution in Seepage Process

Dan Li¹, Chunguang Fei¹, Lihui Wang² and Huifen Xia², *

¹Research Institute of Exploration and Development of Daqing Oilfield Company Ltd., Daqing, China
²School of Petroleum Engineering, Northeast Petroleum University, Daqing, China

*Corresponding author e-mail: 757581676@qq.com

Abstract. Using seepage experiments and theoretical methods, the pseudo-residual resistance factor is introduced, the working viscosity calculation method is modified, and the influence of the viscosity and injection speed of the polymer solution on the change of working viscosity in porous media with different permeability is studied. The pseudo-residual resistance factor calculation is more reasonable to describe the dynamic change of working viscosity during the displacement process; as the permeability and viscosity of the injection fluid increase, the working viscosity of the polymer in the porous medium increases; as the injection speed increases, the polymer shows Viscoelasticity, working viscosity shows a trend of decreasing first and then increasing.

1. Introduction

Polymers are widely used to enhance oil recovery. The main oil displacement mechanism is to increase the range of displacement through the viscosity-increasing effect of the solution, effectively suppress the viscous fingering phenomenon, and significantly improve the mobility ratio. Therefore, the effective working viscosity of the polymer in the formation is a key factor affecting the effect of controlling mobility. The seepage characteristics of polymer solutions in porous media are very complicated. It depends not only on the properties of the polymer solution itself but also on the pore structure characteristics of the formation. During the process of polymer injection, the adsorption, traps, and the retention effect are dynamically changing.

Zhongbin Ye et al [1-5]have shown that after shearing polymer molecules through a porous medium, the molecular chain of the polymer is destroyed to a certain extent, which affects the performance of the polymer solution; Huifen Xia et al[6-7] studied the viscoelasticity of the polymer solution during the seepage process, and gave the expression of the apparent viscosity of the viscoelastic polymer solution and the critical shear rate when showing elasticity; Binhui Li et al[8] studied the calculation formula of shear rate, considering the coefficient of permeability decline and the volume of inaccessible pores during stable seepage, and the calculation result is more scientific and accurate. ByungIn Choi et al. Considered the rheological properties of polymer solutions. The newly proposed working viscosity model shows that the viscosity loss of the polymer is proportional to the initial concentration. Pavlos S Stephanou, Martin Krger et al. Derived analytical formulas for shear rate and linear viscoelastic behavior. These methods of calculating working viscosity generally use the residual resistance coefficient of the formation when the formation reaches saturation saturation, and didn't consider the influence of the
residual resistance coefficient on the working viscosity due to the adsorption and retention of polymer solution during injection. In this paper, the concept of the pseudo-residual resistance coefficient is proposed, and the change of the pseudo-residual resistance coefficient with the number of injected PV is studied through core seepage experiments. Also, the working viscosity of the polymer solution during the seepage process was calculated, and the changing laws and influencing factors of the working viscosity were analyzed.

2. Experiment

2.1. Materials
Polymer: polyacrylamide, relative molecular weight 800×10^4, effective content and 90%; experimental water: NaCl content is 4500mg/L, all filtered through 0.45 filter membrane before use. Experimental core: natural beret core, the core size is φ2.5cm×10cm, and the effective permeability Kw is in the range of 50~150×10^{-3}μm^2. Experimental instruments: a set of core displacement systems such as thermostat, ISCO pump, core holder, intermediate container, precision pressure gauge, filtration device, HAKE rheometer, and confining pressure pump.

2.2. Procedure
(1) Determine the core permeability and porosity and other parameters, and place the core in the incubator for more than 8h after evacuating and saturating the formation water;
(2) Assemble the experimental process, put the core into the core holder and empty the air;
(3) Inject water at a constant flow rate until the pressure at both ends of the core is stable. Increase the injection rate until the pressure at both ends of the core is stable. Repeat the above steps to measure the permeability of the core;
(4) Inject simulated water at a constant flow rate until the pressure at both ends of the core is stable; then inject polymer solution 3 ~ 5PV until the pressure at both ends of the core is stable, record the pressure and flow at both ends of the core, then gradually increase the injection speed and record it again until all the experimental points are measured;
(5) According to the experimental data, calculate the residual resistance factor and the working viscosity of the polymer solution in the porous medium.

2.3. Plan
The injection fluid viscosity is 20, 40, 60mPa·s, the seepage experiment is carried out in the core with the effective permeability of 53, 105, 154mD. When studying the effect of injection speed on the working viscosity of the polymer, The displacement rate is 2, 16, 32, 64ml /h. the displacement rate is 6ml / h for other experiments.

3. Results and analysis

3.1. Seepage characteristics
The polymer with a viscosity of 40mPa·s was used to conduct a seepage experiment in a core with an effective permeability of 105 mD. The injection pressure at different stages varies with the injection amount as show in Figure 1. It can be seen from the figure that if the polymer solution is to reach adsorption saturation and the pressure is stable, the polymer solution to be injected is above 3.6PV. According to Figure 1, the residual resistance coefficient is calculated. The residual resistance coefficient of the polymer solution is defined as $R_{kk} = \frac{\Delta P_3}{\Delta P_1}$. In the formula: $\Delta P_1$ is steady pressure during water flooding; $\Delta P_2$ is steady pressure during polymer flooding; $\Delta P_3$ is steady pressure during subsequent flooding.

In the actual polymer flooding process, the actual injection volume is generally between 0.69 and 0.75PV. It is difficult to achieve such a high injection PV to stabilize its pressure, and the residual resistance factor calculated from this is not the True reflection of changes in seepage capacity. Therefore,
the ratio of the stable pressure ($\Delta P_3'$) during the subsequent water flooding at different times of polymer injection (0.2, 0.6, 1.0, 1.4PV) to the water flooding stable pressure is defined as the quasi residual resistance coefficient: $R_{kk}'=\Delta P_3'/\Delta P_1$. Its significance is the dynamic process of polymer adsorption and retention in the core at different injection amounts during the displacement process.

![Figure 1](image1.png)

**Figure 1.** Pressure with injection volume at different displacement stages.

According to the above method, the change of the pseudo residual resistance factor with the injection volume is calculated. As can be seen from Figure 2, the pseudo residual resistance factor increases with the increase of the injection volume, and finally tends to be stable. The pseudo residual resistance factor at stability is the residual resistance factor. This also reflects that under different PV injection, the adsorption retention of polymer in the core is a dynamic process. As the injection amount of polymer increases, the adsorption retention increases and gradually tends to saturation, resulting in the permeability of the polymer solution A dynamic descent process. Therefore, the corresponding pseudo-resistance resistance factor under different PV can better reflect the dynamic process of core permeability change.

![Figure 2](image2.png)

**Figure 2.** Pseudo-residual resistance factor changes with injected PV.

### 3.2. Working viscosity calculation

During the seepage process, the polymer is sheared by the pore medium, and the working viscosity is lower than the apparent viscosity \[^{11-13}\]. The shearing effect of the polymer solution is related to the injection rate on the one hand, and the permeability of the porous medium during the polymer flooding process on the other hand. During the displacement process, a part of the polymer will form adsorption and retention on the inner surface of the rock or the tiny pores, resulting in the change of the shear rate of the polymer solution. Calculation formula of working viscosity of polymer solution:

$$\mu_p = K_w \frac{R_{kk}'}{R_{kk}'} \frac{\Delta PA}{QL}$$  \hspace{1cm} (1)

In the formula: $R_{kk}'$ (pseudo) residual resistance factor, (pseudo-residual resistance when the adsorption retention is not saturated, and residual resistance when the adsorption retention is saturated);
From the injection of polymer solution to the stage of stable seepage, the effective permeability of the core is a dynamically changing parameter, so it is not reasonable to use the residual resistance factor during stable seepage to calculate the working viscosity. According to the seepage characteristic curve in Figure 1 and the pseudo-residual resistance coefficient calculated in Figure 2, the working viscosity of the polymer solution in the seepage process is calculated using formula (1). Figure 3 shows the changes of the working viscosity calculated with the injected PV using the residual resistance factor and the pseudo-residual resistance factor, respectively.

When the residual resistance factor is used to calculate the working viscosity, as the injected PV increases, the working viscosity of the polymer solution in the porous medium gradually increases until it is stable. This is because at the beginning of the polymer injection stage, due to the small amount of polymer injection, the adsorption retention is small, and the polymer and water flow simultaneously in the core. At this stage, the pressure difference across the core increases slightly compared with water flooding, and the residual The coefficient of resistance is small, and the calculated working viscosity is large. As the injection volume increases, the polymer's adsorption retention in the core gradually increases and reaches saturation, the residual resistance factor tends to stabilize, and the calculated working viscosity also tends to stabilize.

When the pseudo-residual resistance factor is used to calculate the working viscosity, the working viscosity of the polymer solution shows a rising-falling-stable trend with the increase of the injection volume. This is mainly due to the small adsorption and retention of the polymer in the core during the initial period of injection. At this stage, the polymer and water seepage simultaneously, the pressure difference is small, the pseudo-residual resistance factor is small, and the calculated working viscosity is large. When the polymer retention in the core gradually increases, the pressure difference gradually increases, the pseudo-residual resistance factor is large, and the calculated working viscosity decreases. When the adsorption retention capacity of the polymer reaches saturation, the pressure difference tends to be stable, the pseudo-residual resistance factor no longer changes, and the calculated working viscosity also tends to be stable. Therefore, it is more reasonable and accurate to calculate the working viscosity by using the pseudo-residual resistance factor at different displacement stages of the polymer solution in the seepage process.

![Figure 3. Using factors to calculate the change rule of working viscosity.](image-url)
to compare the influence of different factors on the working viscosity. Therefore, the residual resistance 
factor during steady seepage is used to calculate the working viscosity and analyze the influence of 
different factors on its changing law.

3.3.1. Permeability. In the flow experiment of the same polymer viscosity (40 mPa·s) and different core 
permeability (53, 105, 154 mD), according to the pressure and other parameters collected during the 
experiment combined with formula (1), the working viscosity of the polymer in the porous medium is 
calculated, and the variation law is plotted as shown in Figure 4. It can be seen that as the permeability 
increases, the working viscosity of the polymer solution in the porous medium also increases. This is 
because working viscosity is a parameter related to shear rate. The lower the permeability, the higher 
the shear rate, and the lower the working viscosity. As the permeability increases, the adsorption 
retention in the pores decreases, and the shearing and stretching effects of the polymer solution during 
the migration in the pore medium become smaller. Therefore, the working viscosity of the polymer 
solution in the porous medium increases.

![Figure 4. Working viscosity changes with core permeability.](image)

3.3.2. Injection fluid viscosity. In the Beret core with an effective permeability of 105 mD, the seepage 
experiments were conducted using polymer solutions of 20, 40 and 60 mPa·s, respectively. Through the 
pressure and other parameters collected during the fluidity experiment, the working viscosity of the 
polymer solution in the porous medium is calculated according to formula (1). It can be seen from Figure 
5 that in the same permeability core, the polymer concentration increases, the viscosity increases, the 
molecular concentration per unit volume increases, the intermolecular and intramolecular forces of the 
polymer increase, and the polymer molecule gyration radius increases. The mutual entanglement 
between the molecular chains is more obvious, the three-dimensional structure is more stable, and it 
shows that the shear resistance is enhanced, the viscosity retention rate in the formation is high, and the 
working viscosity is also increased.

![Figure 5. Working viscosity changes with injection fluid viscosity.](image)
3.3.3. *Injection rate.* Under the conditions of core permeability of 105mD and polymer viscosity of 40mPa·s, the injection rate is 2, 16, 32, and 64mL/h in the flowability experiment, as shown in Figure 6. As the injection rate increases, the working viscosity of the polymer solution decreases first and then increases. This is mainly because the polymer has both shear flow and extensional flow in the porous medium. Within a certain range of seepage velocity, the migration of polymer solution in porous media is mainly based on shear flow. The flow rate increases and the viscosity decreases. The fluid exhibits a pseudoplastic fluid characteristic. When the flow velocity exceeds a certain range, the stretching effect is enhanced, the stronger the entanglement of the polymer molecules, the greater the microscopic force generated during the seepage process, resulting in stronger viscoelasticity, the elastic effect of the polymer solution is greater than the viscous effect, and in view of the increase in injection speed and the increase in working viscosity, this increase is mainly due to elastic viscosity.

![Figure 6. Working viscosity changes with injection rate.](image)

4. *Conclusion*
(1) By defining the pseudo-residual resistance factor to characterize the change of permeability during polymer flooding, the calculated polymer working viscosity is more accurate and scientific.
(2) The working viscosity of the polymer solution in the porous medium increases with the increase of the permeability and the viscosity of the injection liquid.
(3) As the injection speed increases, due to the effect of viscoelasticity, the working viscosity of the polymer tends to decrease first and then increase.

**Acknowledgments**
This work was financially supported by Major science and technology project of CNPC: research and test on EOR technology of three types of oil layers.

**References**
[1] Ye Zhongbin, Wang Xingyuan, Shu Zheng. The effect of shearing on the hydrodynamic radius distribution of polymer solutions [J]. Chemical Research and Application, 2016, 28 (09): 1268-1274.
[2] Shu Zheng, Wang Mai, Ye Zhongbin, Lu Qiang. Multi-stage shearing method for determining the properties of polymer solutions [J]. Science Technology and Engineering, 2016, 16 (13): 182-185.
[3] Guo Guangfan, Ye Zhongbin, Shu Zheng. The effect of shear in the near-well zone on the seepage characteristics of polymer solution for oil displacement [J]. Oil Field Chemistry, 2014, 31 (01): 90-94.
[4] Ye Zhongbin, Jia Tianze, Shi Leiting, Chu Yanjie, Shu Zheng. Research on the fluidity control ability of hydrophobically associating polymers [J]. Journal of Southwest Petroleum University, 2007 (05): 100-104 + 204-205.
[5] Shi Leiting, Xu Haofei, Ye Zhongbin, Xiang Wentao, Zhou Wei, Zhao Wensen. Research on the effect of shearing on the fluidity control ability of different polymer solutions [J]. Oilfield
[6] Xia Huifen, Ma Jiangping, Feng Haichao, Yin Daiyin, Zhang Jiuran, Ma Wenguo. Experimental study on the rheology of polyacrylamide solution in the seepage process [J]. Experimental Technology and Management, 2013, 30 (03): 31-34.

[7] Xia Huifen, Liu Xiaoxiao, Xu Miao, Wang Shenming. Effect of polymer mobility control on oil displacement in heterogeneous reservoirs [J]. Journal of Petrochemical Colleges and Universities, 2015, 28 (03): 70-73 + 85.

[8] Stephanou Pavlos S, Kröger Martin. From intermediate anisotropic to isotropic friction at large strain rates to account for viscosity thickening in polymer solutions. [J]. The Journal of Chemical Physics, 2018, 148 (18).