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Experimental Study on the Effect of ASP Flooding on Improving Oil Recovery in Low Permeability Reservoirs Based on a Partial Quality Tool

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Abstract: In order to solve the problem of the poor oil displacement effect of high molecular weight alkali/surfactant/polymer (ASP) solution in low permeability reservoirs, Daqing Oilfield uses a partial quality tool to improve the oil displacement effect in low permeability reservoirs. In the formation, the partial quality tool degrades the polymer through active shearing action, reducing the molecular weight of the polymer, to improve the matching degree to the low permeability oil layer and the oil recovery. In order to study the ability of the partial quality tool to improve the oil displacement effect, the matching degree of high molecular weight ASP solution to low permeability cores is studied, and the ability of quality control tools to change the molecular weight is studied. Then, experimental research on the pressure and oil displacement effect of high molecular weight ASP solution before and after the actions of the partial quality tool is carried out. The results show that ASP solutions with molecular weights of 1900×10^4 and 2500×10^4 have a poor oil displacement effect in low permeability reservoirs. After the action of the partial quality tool, the injection pressure is reduced by 5.22 MPa, and the oil recovery is increased by 7.79%. The injection pressure of the ASP solution after shearing by the partial quality tool is lower than that of the ASP solution with the same molecular weight and concentration without shearing, but the oil recovery is lower. On the whole, the use of the partial quality tool can obviously improve the oil displacement effect in low permeability reservoirs.

Keywords: ASP flooding; low permeability oil layer; partial quality tool; maximum injection pressure; oil recovery

1. Introduction

The demand for petroleum products in modern society is increasing, and the exploitation of depleted oil fields is increasing. However, with the increase of exploitation time, the oil recovery is decreasing year by year, and the remaining oil content in the formation is relatively large, however, the remaining oil mainly exists in microscopic remaining parts of pores that cannot be swept away by water flooding, so the traditional water flooding is not effective [1]. At present, the chemical flooding method is adopted for oil displacement, which can improve oil recovery to the greatest extent [2]. Alkali/surfactant/polymer (ASP) flooding has the best effect on treating high water cut oil fields [3]. An ASP solution with a high molecular weight and high concentration can greatly improve oil recovery in high permeability oil layers [4]. However, for heterogeneous reservoirs, the injection effect of the displacement agent in high permeability reservoirs is better and the injection amount is greater [5,6], which results in less displacement agent flowing into low permeability reservoirs, and it is difficult for high molecular weight and high concentration displacement agents to enter low permeability reservoirs [7], resulting in a low overall crude oil recovery. For this reason, Daqing Oilfield has proposed a type of injection technology. On the premise of not affecting the oil displacement effect of high molecular weight ASP solution in high permeability oil layers, a partial quality tool is used when ASP solution flows into the low permeability oil layer to improve the oil displacement effect of the ASP solution in the low permeability oil layer through shearing action, thus improving the overall oil recovery.

Some scholars have made relevant studies on the problem of the poor oil displacement effect in low permeability reservoirs. They have proposed the use of hydraulic fracturing technology to change the formation structure and directly change the formation permeability to improve the oil recovery [8]. Zhuang et al. [9] proposed a type of circulating hydraulic fracturing technology and conducted experimental research on Pocheon granite core. The results showed that circulating hydraulic fracturing produces more complex fractures with branches and smaller pore sizes, and the change of permeability is relatively uniform. It is a method to improve formation permeability and oil displacement effect. Zhou et al. [10] used a temporary plugging agent for fracturing and, through simulation experiments and field application, realized multi-cluster stimulation and formed a dense fracture network to maximize the drainage area. They also used liquid nano-fluid as a fracturing fluid additive to improve the oil–water displacement ratio and injected a large amount of fracturing fluid to maximize oil production after hydraulic fracturing. Lu et al. [11] established the capillary pressure model and calculated the stress intensity factor to quantify the potential of the hydraulic fracturing fluid to enhance oil recovery in tight sandstone and shale reservoirs.

Other scholars have improved the oil recovery of low permeability reservoirs by changing the types of displacement agents. At present, CO_2 injection technology is considered to be an effective technology to improve the oil recovery of low permeability reservoirs [12]. Park et al. [13] chose Berea Sandstone and Sarukawa Sandstone to conduct CO_2 flooding experiments in porous sandstone. The results show that when the injected CO_2 reached about 2.0 PV, Berea sandstone's soil recovery was 74.80%, Sarukawa sandstone's oil recovery was 71.39%, and CO_2 diffused into Berea sandstone evenly from the injected part. In Sarukawa sandstone, almost all CO_2 passed preferentially through the upper part of the sample. Chen et al. [14] simulated CO_2 displacement through long core displacement experiments and nuclear magnetic resonance experiments. The results showed that under the current formation pressure (32 MPa), the minimum miscible pressure of CO_2 flooding was 32.6 MPa, the CO_2 solubility of crude oil was large, and after injecting CO_2, the crude oil had a strong swelling capacity, which was conducive to improving the oil recovery. Liu et al. [15] measured the saturation pressure and oil–gas volume ratio of two crude oil samples with different CO_2 injection rates in PVT pools and three reservoirs with different permeability and low permeability. The experimental results show that the dissolution of CO_2 significantly increased the saturation pressure of oil, the gas–oil volume ratio, and greatly increased the influence of reservoir cores on the oil phase balance, which helped to enhance the oil recovery.

Although the above methods can effectively improve the oil displacement effect of low permeability reservoirs, they still have many deficiencies. For hydraulic fracturing technology, it is difficult to recover the used fracturing fluid after injection into the formation. If it stays in the formation, it will block the pore canal and form seepage resistance at the staying place, which will affect the oil displacement effect, and it will also pollute the formation and form secondary pollution [16,17]. For CO_2 flooding, the process of transporting CO_2 will cause structural damage and corrosion of pipelines, and gas channeling will occur during the oil displacement process, reducing the sweep efficiency [18–20]. Therefore, under the condition of not changing the structure of the low permeability oil layer and not polluting the oil layer, it is of great significance to use a partial quality tool to improve the oil displacement effect. At this stage, Huang et al. [21] constructed the rheological model for polymer solution using the partial quality tool and determined the maximum injection speed of polymers. Their research showed that the structural parameters of the partial quality tool affect the range of apparent viscosity of the polymer solution and directly affect the oil displacement effect of the polymer solution. Huang et al. [22] studied the changes in the molecular micro-morphology and physical parameters of the ASP solution before and after it flowed through the partial quality tool through micro-experiments and shear tests. The research results provided an experimental basis for the research on the effect of the separation tool and the improvement of the oil recovery of the ASP solution in low permeability reservoirs. However, these studies only addressed the theoretical and microscopic mechanisms of the partial quality tools. An experiment using the partial quality tool to improve the oil recovery of low permeability reservoirs in the oil displacement experiment has not been carried out, and the degree of influence on the oil recovery is still unknown. Therefore, it is necessary to conduct oil displacement experiments from the point of view of actual production and consider the influence of different polymer solutions and oil layers with different permeability on the oil displacement process of partial quality tools, which provides a thought and technical methods for later research on using physical methods to improve the oil recovery of heterogeneous reservoirs.

This paper studies the injection ability and oil displacement effect of an ASP solution with a high molecular weight in low permeability cores and determines the matching relationship between molecular weight and cores, firstly. According to the matching relation, the shearing effect of the partial quality tool on ASP solutions with different molecular weights is studied, the influence range of the partial quality tool on the molecular weight is determined, and the molecular weight to be used in the experiment is selected. Then, through laboratory displacement experiments, the injection pressure and displacement effect of the ASP solutions with different molecular weights in cores with different levels of permeability before and after the actions of the partial quality tool are studied, and the injection pressure and displacement effect of an ASP solution with the same molecular weight and concentration but without shearing action of the partial quality tool are compared. The research results are of great significance for improving the oil recovery of low permeability reservoirs.

2. Experiment

2.1. Experiment Materials

2.1.1. Core

The experimental core was provided by the No.1 Oil Production Plant of Daqing Oilfield. The core was made of quartz sand and clay and was externally cemented with epoxy resin. The permeability levels of the cores used were 50×10^{-3}, 100×10^{-3}, 200×10^{-3}, and 600×10^{-3} μm^2, respectively, with a porosity of 22–29%, oil saturation of 69–77%, and core specifications of 30 cm long, 4.5 cm wide, and 4.5 cm high.

2.1.2. Brine

The ASP solution was diluted with prepared brine, and the core was saturated with formation brine in the displacement experiment. The prepared brine and formation brine were provided by the No.1 Oil Production Plant of Daqing Oilfield, and the compositions of the two kinds of brine are shown in Table 1.

Table 1. Composition of brine.

Component Brine Type	NaCl	KCl	$CaCl_2$	$MgSO_4$	Na_2SO_4	$NaHCO_3$	Total Mineralization
Prepared brine (mg/L)	796	396	201	116	114	144	1767
Formation brine (mg/L)	1209	501	224	131	169	175	2409

2.1.3. Experimental Oil

The oil for the displacement experiment was provided by the No.1 Oil Production Plant of Daqing Oilfield and was made by mixing crude oil produced by the No.1 Oil Production Plant with aviation kerosene in a certain proportion. The viscosity of the oil for the experiment at 45 °C was 8.2 MPa.

2.1.4. ASP Solution

The polymer used to prepare the ASP solution in this experiment was partially hydrolyzed polyacrylamide with relative molecular weights of 800×10^4, 1200×10^4, 1600×10^4, 1900×10^4, and 2500×10^4, respectively, and the degree of hydrolysis was about 24% and was provided by the Daqing Refining and Chemical Company. Alkylbenzene sulfonate was used as a surfactant with a purity of 98% and was provided by Daqing Refining and Chemical Company. NaOH was used as an alkaline substance with a purity of 85% and was provided by Daqing Refining and Chemical Company. After the preparation was completed, the solution was dilated with prepared brine to make the ASP solution concentrations reach 1000, 1200, and 1600 mg/L, respectively.

2.1.5. Different Medium Injection Tool

The quality dividing tool used in the experiment was provided by the Daqing Oilfield Oil Production Engineering Research Institute and was made of 304 stainless steel. The structure is shown in Figure 1.

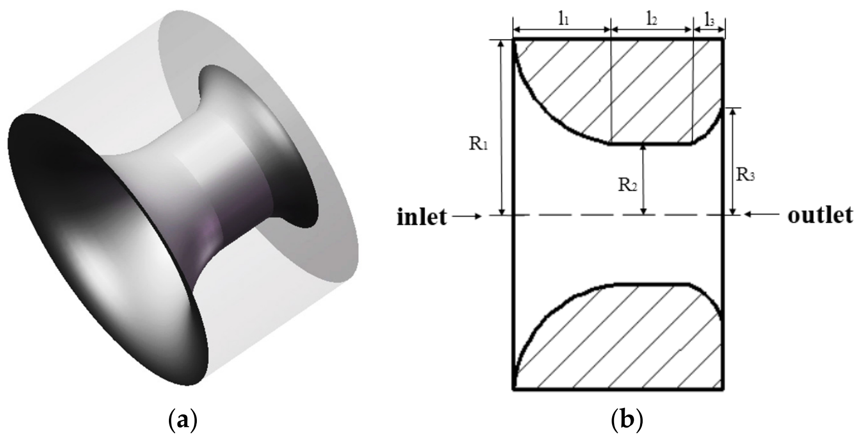


Figure 1. Structural model of the partial quality tool: (**a**) three-dimensional model of the partial quality tool; (**b**) two-dimensional cross-sectional model of the partial quality tool.

The partial quality tool is mainly divided into a contraction section, a cylinder section, and a diffusion section. The middle part of the tool is a region through which the solution flows. During the flowing process, the shearing force of the ASP solution increases rapidly due to the sharp change in the cross-section, resulting in molecular chain fracture, a lowering of the molecular weight, and an improvement of the injection capacity of high molecular weight ASP solution in low permeability oil layers. The structural parameters of the partial quality tool used in the experiment are shown in Table 2.

Table 2. Structural parameters of the partial quality tool.

Contraction Radius R_1 (mm)	Contraction Length l_1 (mm)	Cylinder Length l_2 (mm)	Cylinder Radius R_2 (mm)	Diffusion Length l_3 (mm)	Diffusion Radius R_3 (mm)
3	3	2	2	1	3
4	3	2	2	1	3
5	3	2	2	1	3

2.2. Experimental Procedure

2.2.1. Molecular Weight Measurement Experiment

As shown in Figure 2, the prepared ASP solutions with different molecular weights and different concentrations were put into the liquid storage tank in batches, the valve was opened to start the liquid supply pump, and the flow rate was controlled to be 20, 30, 40, or 50 m^3/d respectively. After passing through the partial quality tool, the solution flowed back to the return liquid tank, and then the ASP solutions in the liquid storage tank and return liquid tank were sampled for testing.

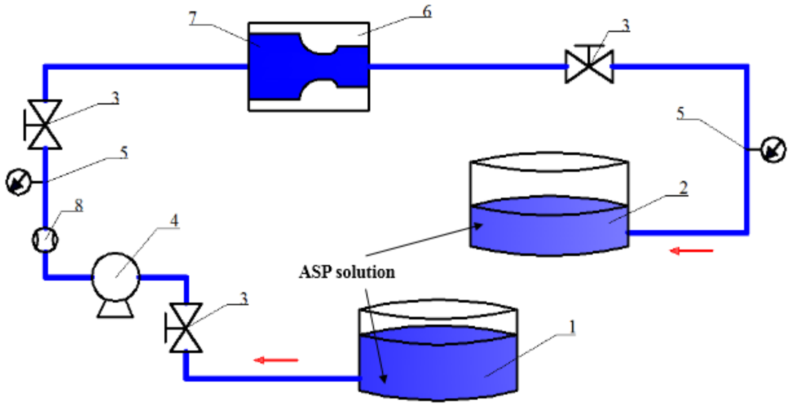


Figure 2. Molecular shearing process: 1—liquid storage tank; 2—return liquid tank; 3—valve; 4—liquid supply pump; 5—pressure gauge; 6—flow simulation chamber; 7—partial quality tool; 8—flow meter.

Using the Zimm light scattering theory, the molecular weight of a polymer can be obtained more accurately. Static light scattering was used to characterize the absolute molecular weight of the polymer. A laser light scattering instrument (BI-200SM, provided by Brookhaven Instruments, as shown in Figure 3) was used to measure the molecular weight of the sampled ASP solution. During the measurement process, a dust-free environment was maintained.

Figure 3. Multi-angle laser light scattering instrument.

2.2.2. ASP Solution Displacement Experiment

The oil displacement experiment process is shown in Figure 4. In order to simulate the real experimental environment, in the experiment, except for the injection system, other equipment was placed in a thermostat at a temperature of 45 °C.

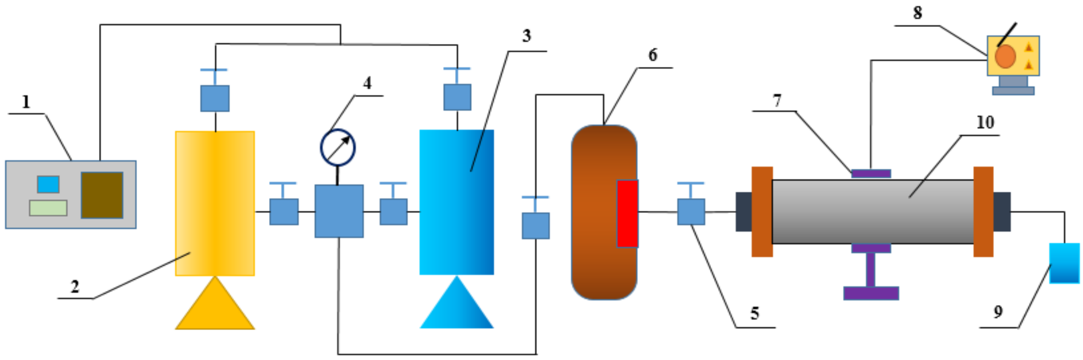
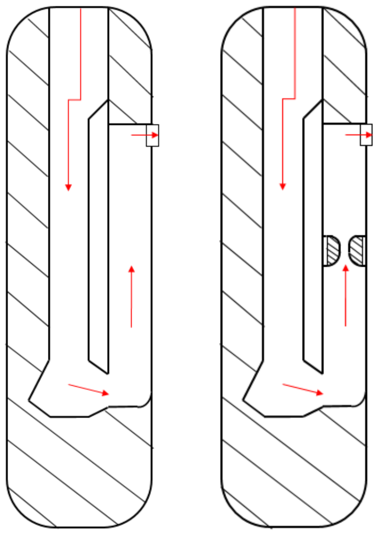


Figure 4. Experiment process: 1—constant-flux pump; 2—piston container 1 (alkali/surfactant/polymer (ASP) solution); 3—piston container 2 (formation brine); 4—pressure gauge; 5—check valve; 6—chemical injector (partial quality tool); 7—core holder; 8—hand pump; 9—beaker; 10—core.

The cores shown in Figure 4 were replaced with cores of different permeabilities according to experimental requirements. The concentration and molecular weight of ASP solution in piston container 1 were changed according to experimental requirements, and formation brine was injected into piston container 2. The partial quality tool was installed or not installed in the chemical injector according to the experimental requirements. The chemical injector in which the partial quality tool was either not installed or installed is shown in Figure 5.



(**a**) (**b**)

Figure 5. Chemical injector: (**a**) chemical injector without partial quality tool; (**b**) chemical injector with a partial quality tool.

The displacement experiment procedure used was as follows:

(1) Artificial cores with different permeability levels were prepared and numbers were recorded.

(2) The core was vacuumed for 4 h, and then the formation brine was saturated and the porosity was measured.

(3) The core was placed in a thermostat and the temperature was kept at 45 °C for 12 h.

(4) The core was saturated with oil. Under the same conditions, the oil displaced water until the outlet of the model did not produce water.

(5) The chemical injector was not installed with a partial quality tool for water flooding to simulate the actual water cut on-site, and the water cut at the outlet of the model reached 98% at a constant flooding speed.

(6) When the subsequent water flooding reached 98% water cut at the outlet end, the experiment was stopped, the maximum pressure in the flooding process was recorded, and the oil recovery of each stage was calculated.

(7) The chemical injector was installed with a partial quality tool and the above experimental steps were repeated. Additionally, the maximum pressure in the displacement process was recorded and the oil recovery of each stage was calculated.

3. Results and Discussion

3.1. Study on the Matching Relationship between the Molecular Weight of the ASP Solution and Core Permeability in the Oil Displacement Experiment

The core displacement experiment was carried out without the use of the partial quality tool. The experimental process is shown in Figure 4, and the relationships among different ASP solutions and the maximum injection pressure and oil recovery were obtained, as shown in Figures 6 and 7.

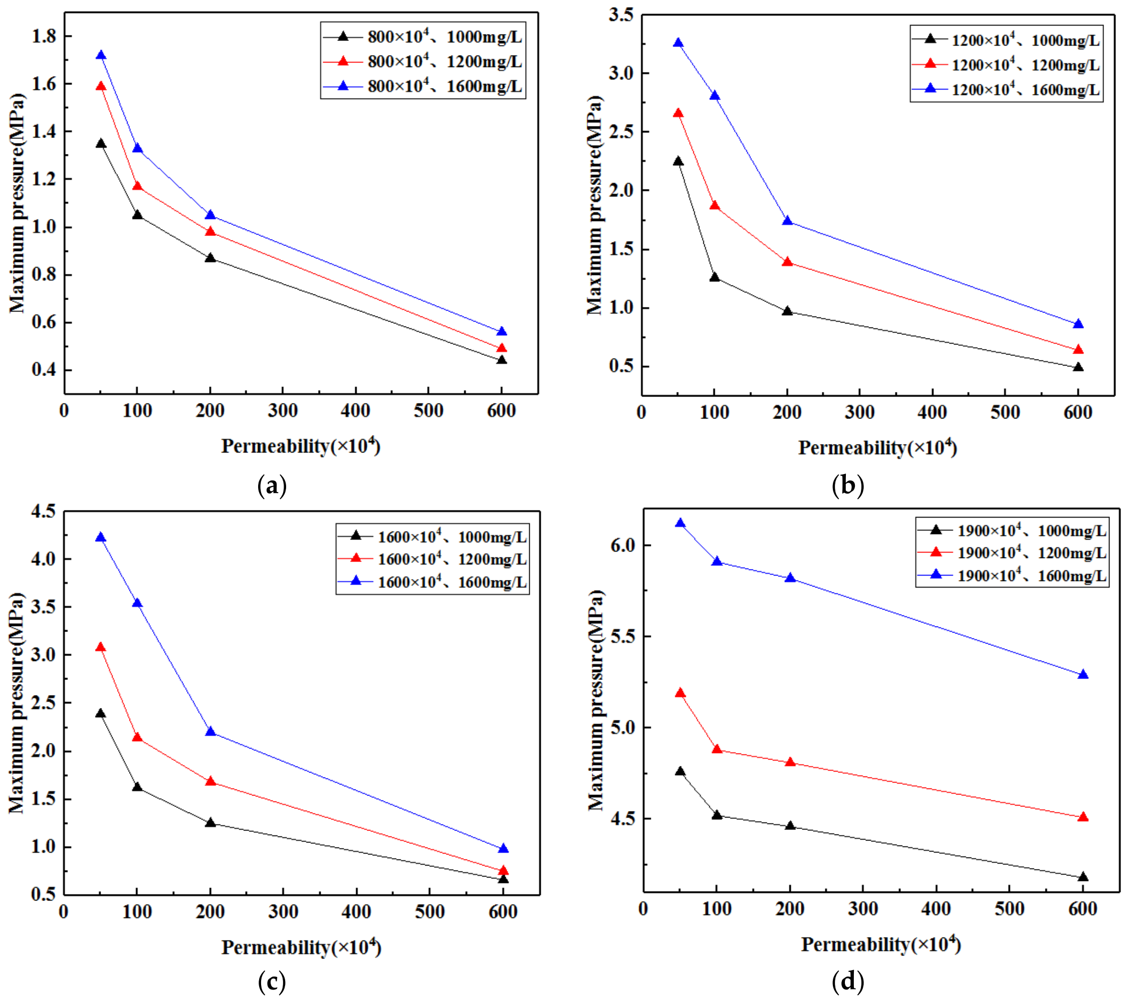
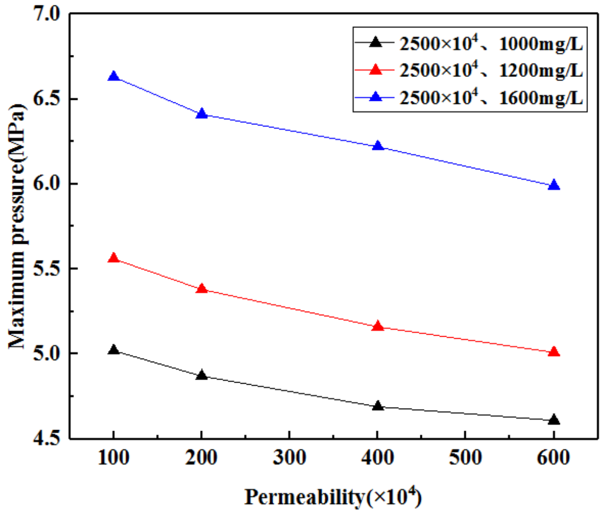


Figure 6. *Cont.*



(**e**)

Figure 6. Maximum injection pressure of the core with different permeabilities injected by different ASP solutions: (**a**) maximum injection pressure of the ASP solution with a molecular weight of 800 × 10^4; (**b**) maximum injection pressure of the ASP solution with a molecular weight of 1200 × 10^4; (**c**) maximum injection pressure of the ASP solution with a molecular weight of 1600 × 10^4; (**d**) maximum injection pressure of the ASP solution with a molecular weight of 1900 × 10^4; (**e**) maximum injection pressure of the ASP solution with a molecular weight of 2500 × 10^4.

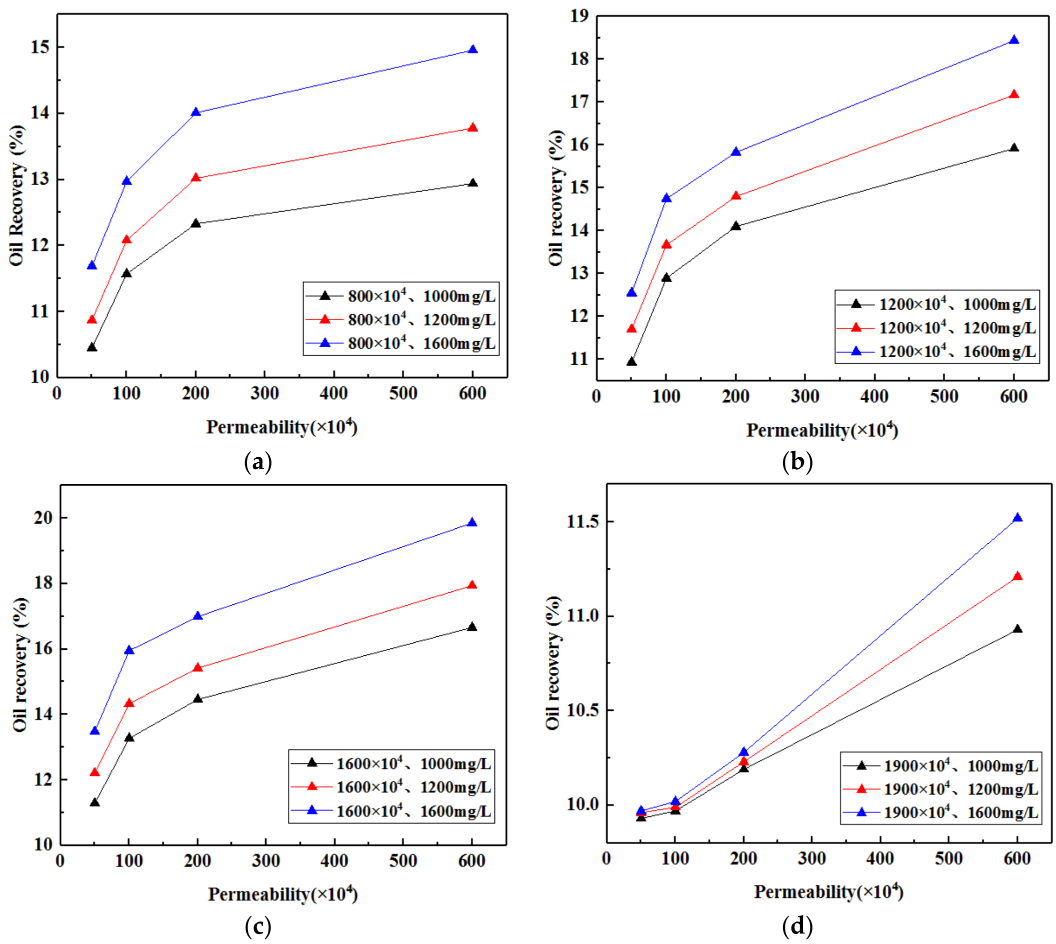
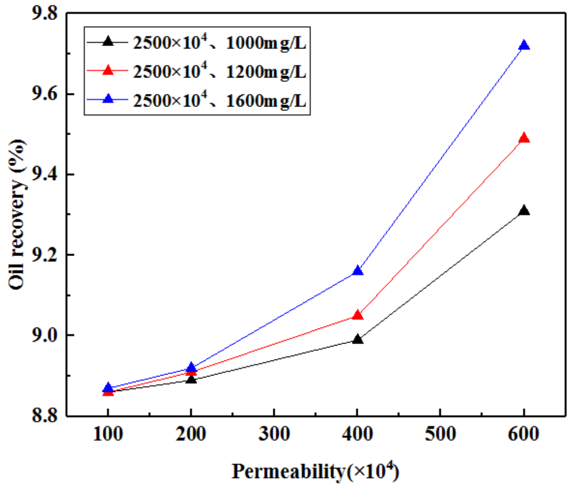


Figure 7. *Cont.*



(**e**)

Figure 7. Final oil recovery of the core with different permeability levels injected by different ASP solutions: (**a**) final oil recovery of the ASP solution with a molecular weight of 800×10^4; (**b**) final oil recovery of the ASP solution with a molecular weight of 1200×10^4; (**c**) final oil recovery of the ASP solution with a molecular weight of 1600×10^4; (**d**) final oil recovery of the ASP solution with a molecular weight of 1900×10^4; (**e**) final oil recovery of the ASP solution with a molecular weight of 2500×10^4.

As can be seen from Figure 6, with the increase of core permeability, the maximum injection pressure of the ASP solution decreases. This is because the larger the core permeability is, the larger the pore volume of the core is, the larger the flow surface of the ASP solution in the core is, the smaller the flow resistance is, and the stronger the injection capacity of the solution is. Therefore, the less injection pressure required, the lower the maximum injection pressure will be [23].

With the increase in the solution concentration, the maximum injection pressure increases. This is because with a higher solution concentration, larger molecular coils will be generated between molecules and more polymers will stay or even block the pore channels, causing difficulties in the injection of the ASP solution, resulting in an increase in the injection pressure. With the increase of the molecular weight, the maximum injection pressure increases. This is because the larger the molecular weight of the polymer is, the larger the effective volume of the molecule in the solution is, and the larger the amount of adsorption and capture in the core are. The obvious permeability reduction effect occurs, resulting in a decrease in the injection capacity. The required injection pressure increases, and the maximum injection pressure correspondingly increases [24]. However, when the molecular weight reaches 1900×10^4 and 2500×10^4, the maximum injection pressure reaches 6.12 and 6.63 MPa, respectively and the minimum is 4.18 and 4.61 MPa, respectively, with the change of concentration, which are both very-high pressure values, and with the increase of permeability, the maximum injection pressure decreases to a lesser extent. This shows that ASP solutions with molecular weights of 1900×10^4 and 2500×10^4 have a poor injection ability with low and medium permeability and a low matching degree to the oil layer, and the effect of changing the solution concentration to change the injection ability of the polymer ASP solution is not obvious.

As can be seen from Figure 7, with an increase in core permeability, the oil displacement effect of the ASP solution is better, and the oil recovery is higher. This is because the higher the core permeability, the larger the pore volume, and the larger the volume of ASP solution entering the core pores, the better the oil displacement effect is. The higher the concentration of the ASP solution, the higher the oil recovery is. This is because the higher the concentration of the solution, the denser the arrangement of polymer molecules, the tighter the overall network structure, the more molecules per unit volume, the greater the viscosity, and the better the oil displacement effect in pores. The higher the molecular weight is, the higher the oil recovery is. This is because the higher the molecular weight, the longer the molecular weight, the easier the molecular weights tangle with each other, the coarser the molecular structure, the higher the viscosity of the solution, and the better the oil displacement effect [25]. However, with the increase of core permeability, ASP solutions with molecular weights of 1900×10^4 and 2500×10^4 have little change in oil recovery, and the change in concentration has little effect on the oil recovery. The oil recovery changes only by 9.93–11.52% and 8.86–9.72% respectively, and the oil displacement effect of the ASP solution with a molecular weight of 2500×10^4 is lower than that of ASP solution with a molecular weight of 1900×10^4, which indicates that the matching degree of polymers in low and medium permeability reservoirs is poor and greatly affects the oil displacement effect.

A comprehensive analysis of the core permeability and the influences of different ASP solutions on the maximum injection pressure and oil recovery showed that when a high molecular weight ASP solution is used for oil displacement, the oil displacement effect is better in high permeability reservoirs, but when it flows into medium and low permeability reservoirs for oil displacement, ASP solutions with molecular weights of 1900×10^4 and 2500×10^4 have a poor injection ability and low oil recovery for low and medium permeability reservoirs, and the improvement of oil displacement effect is not obvious when the concentration is changed. Therefore, for high molecular weight ($>1600 \times 10^4$) ASP solutions, a partial quality tool is used to improve the oil displacement effect of medium and low permeability cores.

3.2. Influence of the Partial Quality Tool on the Molecular Weight of the ASP Solution

In order to improve the oil displacement ability of the polymer ASP solution in cores with medium and low permeability, the shearing action of the polymer ASP solution ($>1600 \times 10^4$) was carried out by using a partial quality tool to break the polymer chain, reduce the molecular weight, and improve the injection ability. According to the research in the above section on the matching relationship between the molecular weight of the ASP solution and core permeability, it can be seen that the concentration change has no obvious effect on the injection capacity and oil displacement effect of high molecular weight ASP solution in medium and low permeability cores. In order to facilitate an experimental comparison after the action of the partial quality tool, three ASP solutions with reduced molecular weight and concentration were selected respectively, that is, an ASP solution with a molecular weight of 2500×10^4 and a concentration of 1600 mg/L, one with a molecular weight of 1900×10^4 and a concentration of 1200 mg/L, and one with a molecular weight of 1200×10^4 and a concentration of 1000 mg/L. The experimental design used different flow rates (20, 30, 40, and 50 m^3/d), and different ASP solutions were sheared under the actions of different structural parameters (contraction radius 3, 4, and 5 mm) and the average molecular weight of the solution was measured by a laser light scattering instrument. The results are shown in Table 3.

Table 3. Changes in the molecular weight of the ASP solution after being acted on by the partial quality tool.

Contraction Radius (mm)	Flow Rate (m^3/d)	Molecular Weight of the 2500×10^4, 1600 mg/L ASP Solution after Shearing ($\times 10^4$)	Molecular Weight of the 1900×10^4, 1200 mg/L ASP Solution after Shearing ($\times 10^4$)	Molecular Weight of the 1200×10^4, 1000 mg/L ASP Solution after Shearing ($\times 10^4$)
3	20	1680	1216	744
	30	1490	1035	609
	40	1312	952	513
	50	1194	871	461
4	20	1958	1524	917
	30	1732	1310	761
	40	1476	1145	636
	50	1380	1065	620
5	20	2305	1762	1060
	30	2178	1555	910
	40	1873	1453	856
	50	1778	1304	734

It can be seen from Table 3 that the smaller the contraction radius is and the larger the flow rate is, the smaller the molecular weight after shearing is. This is because the smaller the contraction radius is, the smaller the flow cross-section of ASP solution in the partial quality tool will be, and the greater the degree of mutation will be, which will strengthen the shearing effect on the solution. With the increase in the flow rate, the velocity gradient of the ASP solution in the partial quality tool will increase, the flow resistance will increase, the shearing effect will also increase, and the more serious the shearing damage to the molecular chain will be, resulting in a decrease in the molecular weight. Additionally, the molecular weight of the 2500×10^4, 1600 mg/L ASP solution can reach (1194–2305) $\times 10^4$ after shearing, and the molecular weight of the 1900×10^4, 1200 mg/L solution can reach (871–1762) $\times 10^4$ after shearing. The molecular weight of the 1900×10^4, 1200 mg/L ASP solution can reach (461–1060) $\times 10^4$ after shearing. This shows that the shearing action of the high molecular weight ASP solution by the partial quality tool is stronger, and the molecular weight decreases to a greater extent. This is because the larger the molecular weight, the longer the molecular chain, the greater the degree of shearing, and the greater the degree of molecular weight reduction [26,27].

In the experiment, in order to obtain the molecular weight corresponding to the initial ASP solution after shearing, the molecular weight of 2500×10^4 can be sheared into 1200×10^4 and 1600 $\times 10^4$; the molecular weight of 1900×10^4 can be sheared into 800×10^4, 1200×10^4, and 1600×10^4; and the molecular weight of 1000×10^4 can be sheared into 800×10^4 by controlling the flow rate and contraction radius, i.e., the molecular weight of the ASP solution can be matched before and after the action of the partial quality tool, which is convenient for comparing the solution properties under the same conditions.

3.3. Influence of the Molecular Weight of the ASP Solution on the Injection Pressure after the Action of the Partial Quality Tool

In order to study the improvement of the core injection ability of ASP solutions with different molecular weights after the action of the partial quality tool, the injection pressure was selected during oil displacement as the verification parameter. According to the influence of the partial quality tool on the molecular weight of the ASP solution, in order to compare the influence of the high molecular ASP solution after shearing with that of the low molecular ASP solution without shearing on the injection pressure, four kinds of artificial cores with permeabilities of (50, 100, 200, and 600) $\times 10^{-3}$ μm^2 were selected. Under each core permeability, the ASP solution after high molecular weight shearing (shear from molecular weight 2500×10^4 to 1200×10^4 and 1600×10^4; shear from molecular weight 1900×10^4 to 800×10^4, 1200×10^4 and 1600×10^4; shear from molecular weight 1200×10^4 to 800 $\times 10^4$) and the low molecular weight ASP solution without shearing (molecular weight 1600×10^4, 1200×10^4, 800×10^4) were tested, respectively. By comparing the influences of factors such as the molecular weight of the ASP solution and core permeability on the injection pressure before and after the action of the partial quality tool, the following experimental results were obtained, as shown in Figures 8 and 9.

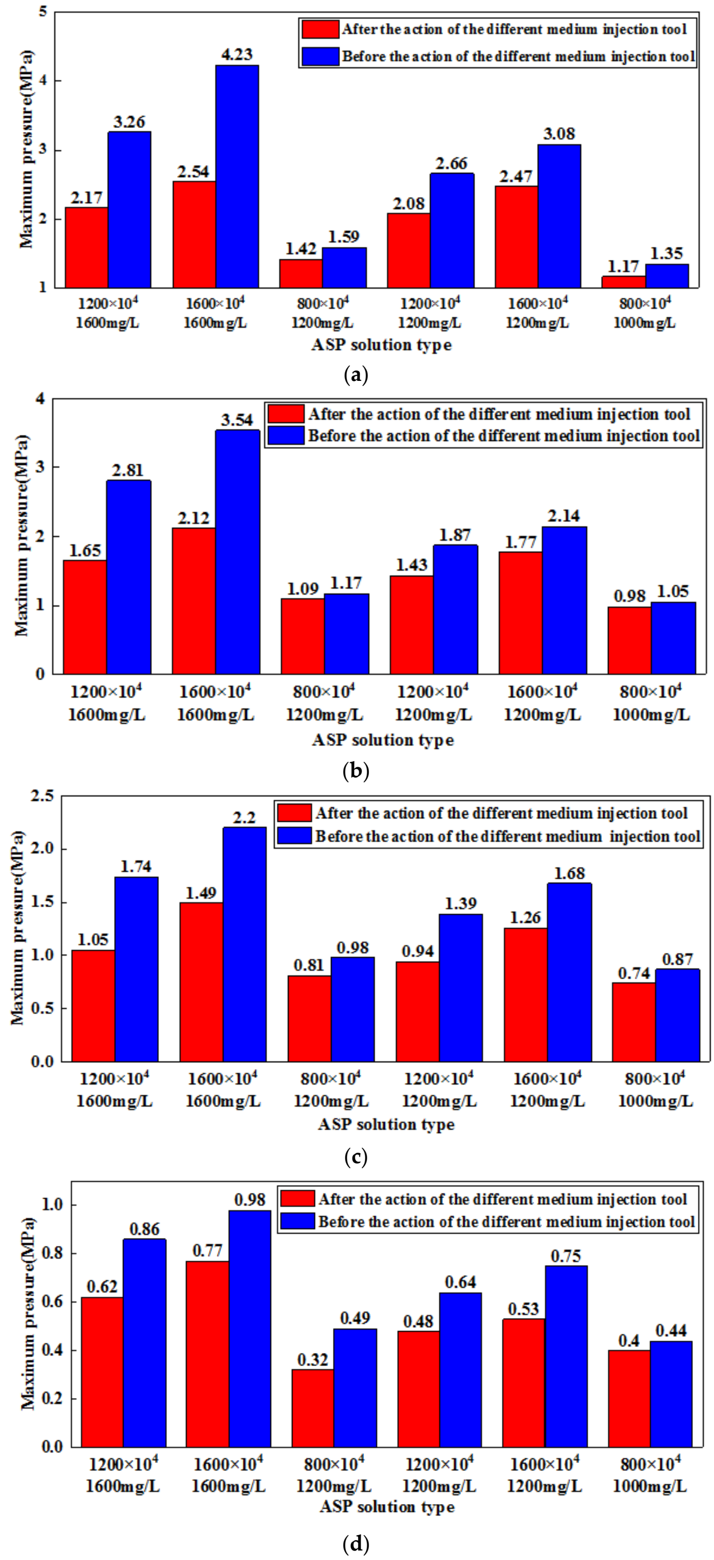
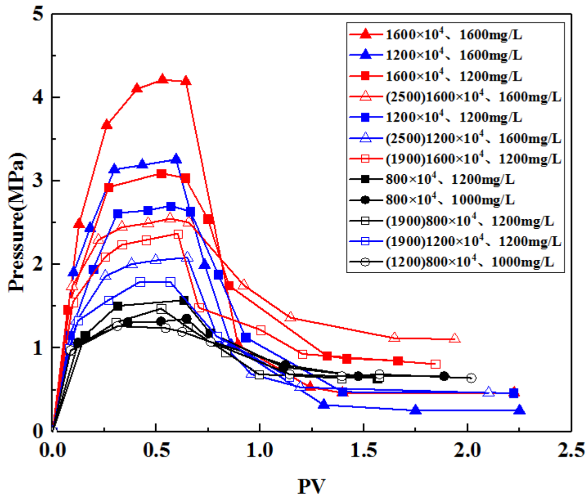


Figure 8. Comparison of the highest pressures of different ASP solutions under different permeabilities before and after the action of the partial quality tool: (**a**) maximum pressures of different ASP solutions with a permeability of 50 × 10^{-3} μm^2; (**b**) maximum pressures of different ASP solutions with a permeability of 100 × 10^{-3} μm^2; (**c**) maximum pressures of different ASP solutions with a permeability of 200 × 10^{-3} μm^2; (**d**) maximum pressures of different ASP solutions with a permeability of 600 × 10^{-3} μm^2.



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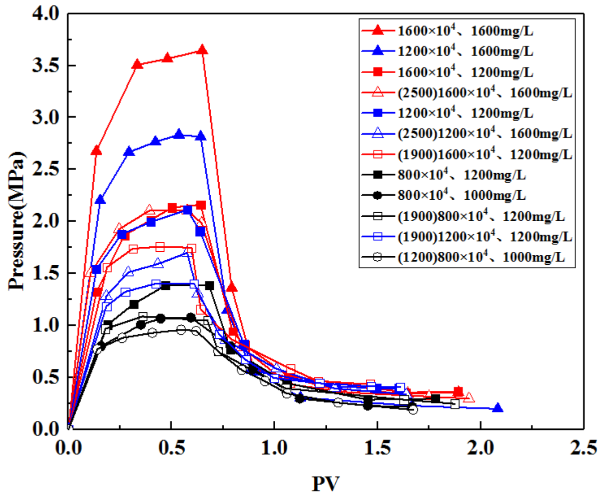

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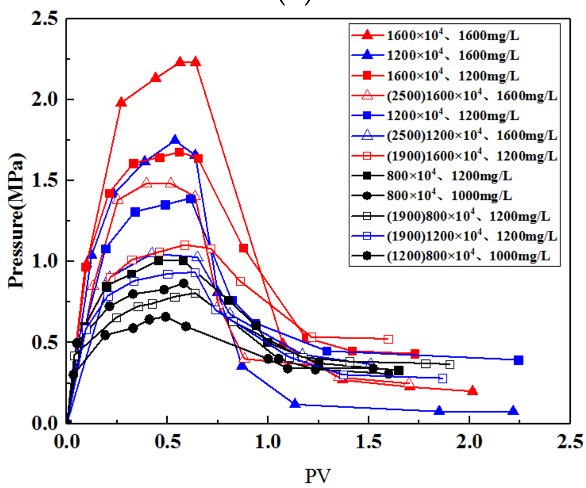

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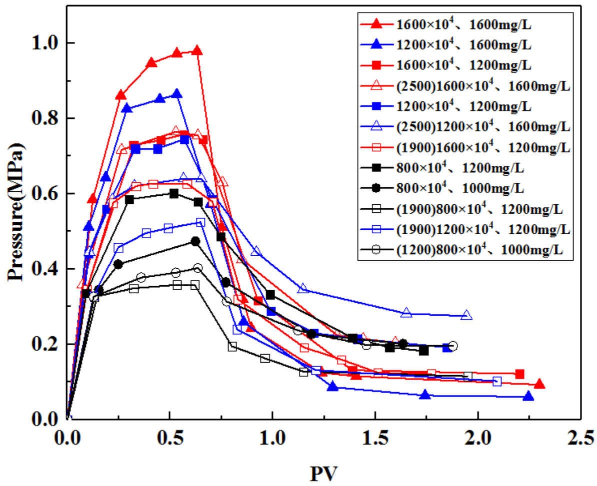
Figure 9. *Cont.*



(**d**)

Figure 9. Comparison of the injection pressures of different ASP solutions under different permeations before and after the action of the partial quality tool: (**a**) injection pressures of different ASP solutions with a permeability of 50 × 10^{-3} μm^2; (**b**) injection pressures of different ASP solutions with a permeability of 100 × 10^{-3} μm^2; (**c**) injection pressures of different ASP solutions with a permeability of 200 × 10^{-3} μm^2; (**d**) injection pressures of different ASP solutions with a permeability of 600 × 10^{-3} μm^2.

As can be seen from Figure 8, when the same ASP solution is injected, the maximum pressure of chemical flooding increases gradually with a decrease in permeability. Moreover, the lower the permeability of the core, the greater the maximum pressure of chemical flooding. An ASP solution with a high molecular weight or high concentration has a high injection pressure due to its high viscosity. In particular, when the permeability is 100 × 10^{-3} μm^2 or 50 × 10^{-3} μm^2, the maximum pressure of chemical flooding is very high, especially for ASP solutions without the shearing action of the partial quality tool, where the maximum pressure of chemical flooding exceeds 4 MPa. At the same permeability, the higher the concentration of ASP solution with the same molecular weight, the higher the maximum pressure. At the same concentration, the higher the molecular weight, the higher the maximum pressure. The reason for this is that at a high concentration or high molecular weight, the viscosity and elasticity of the ASP system increase, and the required injection pressure increases, thus increasing the macro pressure gradient and resulting in an increase in the maximum injection pressure.

For cores with different permeability levels, the ASP solution with a low molecular weight of 800 × 10^4 has a maximum pressure of 0.44–1.59 MPa for chemical flooding without the shearing action of the partial quality tool and a maximum pressure of 0.32–1.42 MPa after the shearing action of the partial quality tool; the ASP solution with a medium molecular weight of 1200 × 10^4 has a maximum pressure of 0.64–3.26 MPa for chemical flooding without the shearing action of the partial quality tool and a maximum pressure of 0.48–2.17 MPa after the shearing action of the partial quality tool; and the ASP solution with a medium molecular weight of 1600 × 10^4 has a maximum pressure of 0.75–4.23 MPa for chemical flooding without the shearing action of the partial quality tool and a maximum pressure of 0.53–2.54 MPa after the shearing action of the partial quality tool.

It can be clearly seen from Figure 9 that for cores with the same permeability, the chemical flooding injection pressure of the ASP solution without the shearing by the partial quality tool is significantly higher than that of the ASP solution with the same molecular weight and concentration after shearing, and the lower the permeability is, the greater the difference is. The injection pressure order in the chemical flooding stage is as follows: medium molecular weight 1600 × 10^4 system > medium molecular weight 1200 × 10^4 system > low molecular weight 800 × 10^4 system. In the 50 × 10^{-3} μm^2 core, the maximum pressure of each system in the chemical flooding stage is higher than 1 MPa. Therefore, for low-permeability cores, the molecular weight of the ASP solution has a great influence on the injection pressure of low-permeability cores. The lower the permeability is, the smaller the pore radius is, and the polymer injection will block the pore channels of the cores, resulting in a higher injection pressure [28].

As shown in Table 4, the pressure of the polymer ASP solution after shearing by the partial quality tool is lower than that of the ASP solution without shearing. The higher the permeability of the core, the more obvious the pressure drop after the action of the partial quality tool is. After shearing, the pressure drop of ASP solutions with molecular weights of 2500×10^4 and 1900×10^4 reached the highest values of 5.22 and 4.03 MPa, respectively, and the higher the molecular weight, the greater the pressure drop after the action of the partial quality tool. This shows that the injection effect of the polymer ASP solution after the action of the partial quality tool is significantly enhanced, and the matching degree to low permeability cores is greater. Therefore, the partial quality tool can obviously improve the injection capacity of the polymer ASP solution and improve the utilization rate of the ASP solution in low permeability cores.

Table 4. Comparison of the maximum injection pressure of the high molecular weight ASP solution before and after the effect of the partial quality tool.

Permeability ($\times 10^{-3}$ μm^2)	Concentration (mg/L)	Molecular Weight ($\times 10^4$)		Maximum Pressure (MPa)
		Before Shearing	After Shearing	
50	1600	2500	1600	2.54
	1600	2500	—	6.63
	1200	1900	1200	2.08
	1200	1900	—	5.19
100	1600	2500	1600	2.12
	1600	2500	—	6.41
	1200	1900	1200	1.43
	1200	1900	—	4.88
200	1600	2500	1600	1.49
	1600	2500	—	6.22
	1200	1900	1200	0.94
	1200	1900	—	4.81
600	1600	2500	1600	0.77
	1600	2500	—	5.99
	1200	1900	1200	0.48
	1200	1900	—	4.51

3.4. Influence of the Molecular Weight of the ASP Solution on the Oil Displacement Effect after the Action of the Partial Quality Tool

In order to study the ability of ASP solutions with different molecular weights to enhance the oil recovery of heterogeneous cores after being acted on by the partial quality tool, relevant experiments were carried out to verify. On the basis of the above maximum pressure experiment, the influences of the polymer ASP solution after shearing and the low molecular ASP solution without shearing on the oil displacement effect were studied. The core permeability and ASP solutions with different molecular weights before and after shearing were the same as those used in the above pressure experiments. By comparing the influence of the molecular weight of the ASP solution and the reservoir permeability before and after shearing on the oil displacement effect, the matching relationship between the ASP solution after shearing and the reservoir permeability is determined, and the following experimental results are obtained, as shown in Figures 10 and 11.

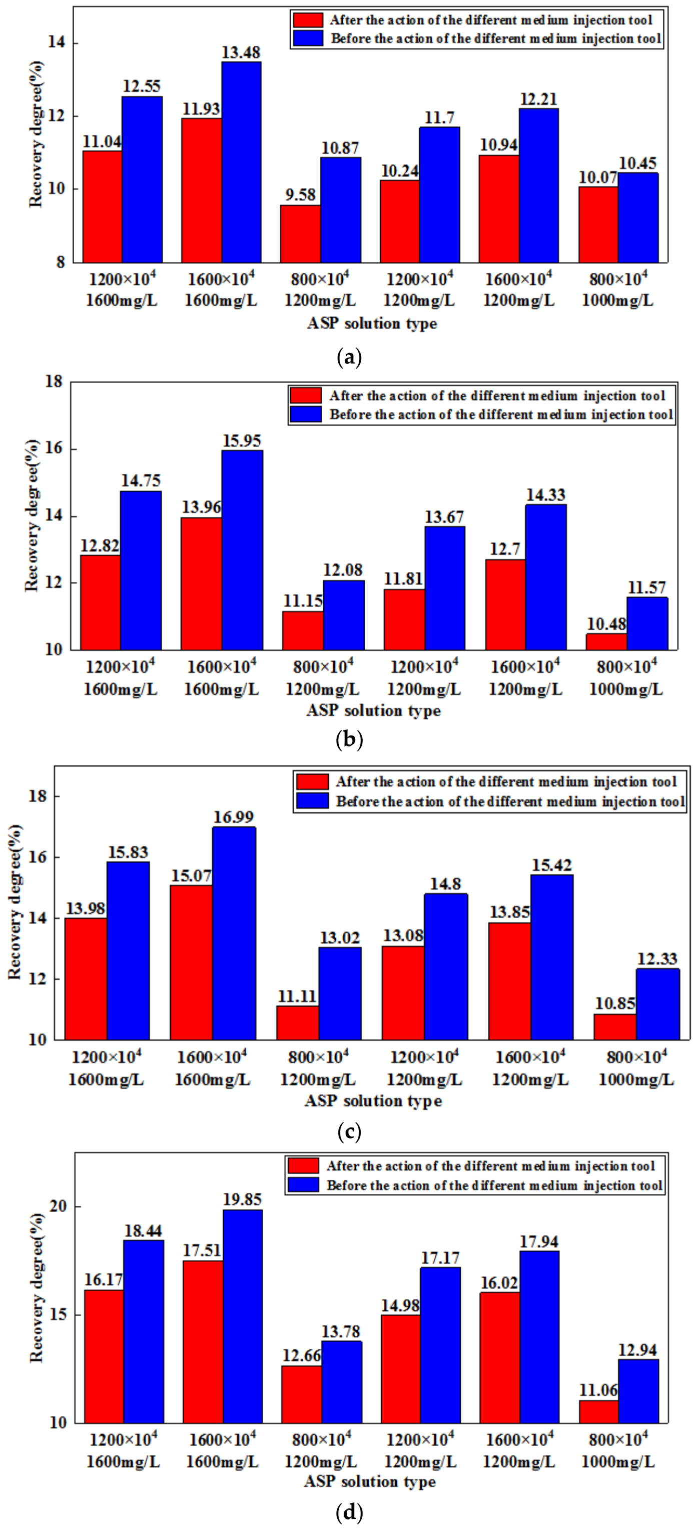


Figure 10. Final chemical flooding oil recovery of different ASP solutions under different permeabilities before and after the action of the partial quality tool: (**a**) final oil recovery of different ASP solutions with a permeability of 50×10^{-3} μm^2; (**b**) final oil recovery of different ASP solutions with a permeability of 100×10^{-3} μm^2; (**c**) final oil recovery of different ASP solutions with permeability of 200×10^{-3}μm^2; (**d**) final oil recovery of different ASP solutions with permeability of 600×10^{-3} μm^2.

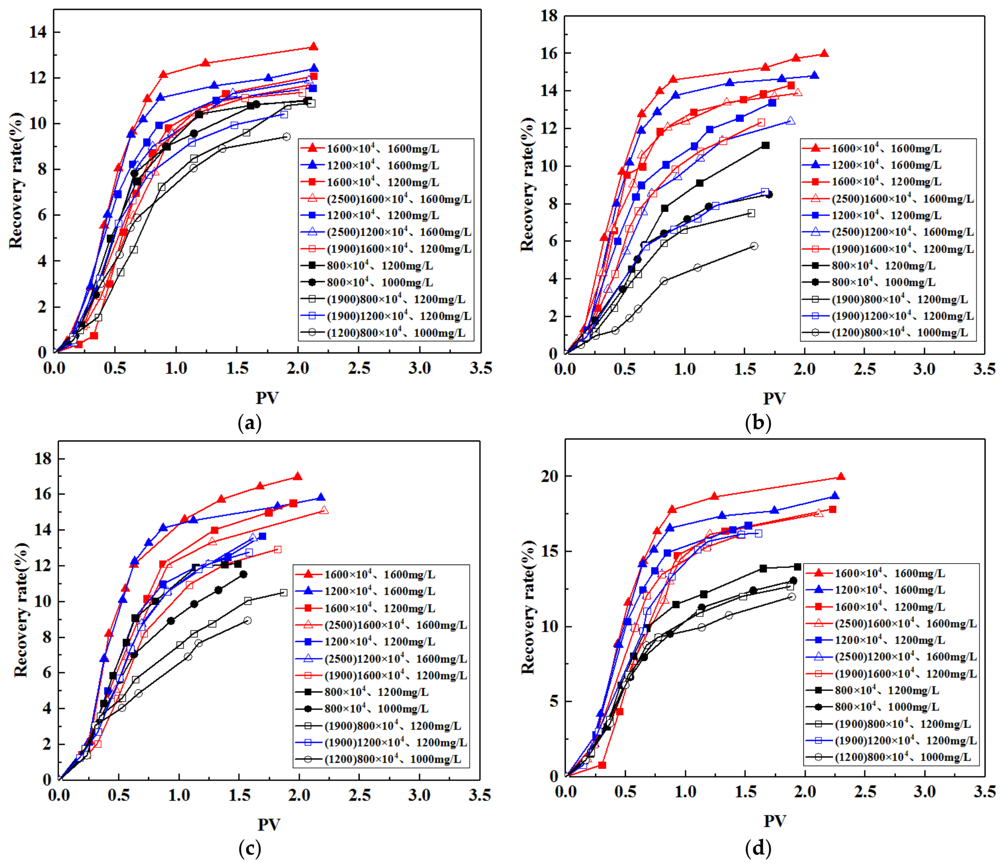


Figure 11. Comparison of the chemical flooding oil recovery of different ASP solutions under different permeabilities before and after the action of the partial quality tool: (**a**) oil recovery of different ASP solutions with a permeability of 50×10^{-3} μm^2; (**b**) oil recovery of different ASP solutions with a permeability of 100×10^{-3} μm^2; (**c**) oil recovery of different ASP solutions with a permeability of 200×10^{-3} μm^2; (**d**) oil recovery of different ASP solutions with a permeability of 600×10^{-3} μm^2.

As can be seen from Figure 10, oil displacement experiments were carried out with ASP solutions of the same molecular weight and concentration in cores with different permeabilities, and the extent of oil recovery improvement was different. No matter how the molecular weight and concentration of polymer in ASP solution change, the higher the permeability is, the greater the extent of chemical flooding to improve the oil recovery is. This is because the higher the permeability, the larger the pore radius and throat of the core, and the more or higher molecular weight ASP solution that enters the pore volume and expands the sweep volume of the displacement agent; thus, its oil recovery is high. Under the same permeability level, the higher the concentration of the ASP solution with the same molecular weight, the higher the oil recovery of chemical flooding. At the same concentration, the higher the molecular weight, the higher the oil recovery of chemical flooding [29,30]. The main reason for this is that when a high concentration or high molecular weight is used, the viscosity of the ASP solution increases, which is helpful for improving the microscopic oil displacement efficiency and the oil recovery in the chemical flooding stage [31].

For cores with different permeability levels, the oil recovery of chemical flooding for the ASP solution with a low molecular weight of 800×10^4 is between 9.58% and 13.78%, regardless of whether it is sheared by the partial quality tool. The oil recovery of the ASP solution with a low molecular weight of 800×10^4 after shearing by the partial quality tool is between 9.58% and 12.66%, and that without shearing by the partial quality tool is between 10.45% and 13.78%. The oil recovery of chemical flooding for the ASP solution with a medium molecular weight of 1200×10^4 is between 10.24% and 18.44%, the oil recovery for the ASP solution with a medium molecular weight of 1200×10^4 after shearing by a partial quality tool is between 10.24% and 14.98%, and that without shearing by the partial quality tool is between 11.7% and 18.44%. The oil recovery of chemical flooding for the ASP solution with a medium molecular weight of 1600×10^4 is between 10.94% and 19.85%, the oil recovery for the ASP solution with a medium molecular weight of 1600×10^4 after shearing by a partial quality tool is between 10.94% and 17.51%, and that without shearing by the partial quality tool is between 12.21% and 19.85%. Therefore, the ASP solution without shearing action of the partial quality tool has a better oil displacement effect than the ASP solution with the same molecular weight and concentration after shearing action.

As can be seen from Figure 11, whether it is a high permeability core or a low permeability core, the best recovery degree of chemical flooding occurs with the high molecular weight ASP solution that has not been sheared by the partial quality tool. The higher the molecular weight and concentration, the greater the recovery degree of chemical flooding. The stage oil recovery is in the following order: medium molecular weight (1600×10^4) system > medium molecular weight (1200×10^4) system > low molecular weight (800×10^4) system. However, the experimental results for $50 \times 10^{-3} \mu m^2$ cores change, and the overall oil recovery is still consistent with other permeability cores. However, the oil recovery in the chemical flooding stage of the ASP solution with a high molecular weight and high concentration is similar to that of the 800×10^4, 1200 mg/L solution without shear, the 800×10^4, 1000 mg/L solution without shear, the 800×10^4, 1200 mg/L solution with shear, and the 800×10^4, 1000 mg/L solution with shear. This shows that although the ASP solution with a high molecular weight and high concentration has better effects of increasing the viscosity and improving the fluidity. The ASP solution with a molecular weight of 800×10^4 after being sheared or not enters more easily into small pores than other high permeability cores, because the pore size in 50×10^{-3} μm^2 cores is obviously lower than that in other high permeability cores, and the sweep range in 50×10^{-3} μm^2 cores is larger, which plays a greater role in expanding the sweep volume and further improving the recovery degree in the chemical flooding stage. Therefore, compared with other systems, the recovery degree is similar. Therefore, the oil recovery of the ASP solution with a shearing action of the partial quality tool is lower than that of the ASP solution with the same molecular weight and concentration without a shearing action.

As shown in Table 5, the oil recovery of the polymer ASP solution with the shearing action by the partial quality tool is greater than that of the ASP solution without shearing. The higher the molecular weight, the more obvious the ability of the partial quality tool to improve the oil recovery is. The chemical flooding recovery of the ASP solution with a high molecular weight (2500×10^4) in a low permeability core (50×10^{-3} μm^2) is only 8.87% at the highest, and the recovery reaches 11.93% after shearing by the partial quality tool. With the increase of core permeability, the recovery after the action of the partial quality tool is higher. The highest recovery of the ASP solution with a high molecular weight reaches 17.51% and the degree of improvement reaches 80.1%. Therefore, the partial quality tool can effectively improve the oil displacement effect of the ASP solution with a high molecular weight.

Table 5. Comparison of the oil recovery of the high molecular weight ASP solution before and after the action of the partial quality tool.

Permeability ($\times 10^{-3} \mu m^2$)	Concentration (mg/L)	Molecular Weight ($\times 10^4$)		Oil Recovery (%)		
		Before Shearing	After Shearing	Water Flooding	ASP Flooding	Total Oil Recovery
50	1600	2500	1600	36.74	11.93	48.67
	1600	2500	—	36.02	8.87	44.89
	1200	1900	1200	37.51	10.24	47.75
	1200	1900	—	37.11	9.96	47.07
100	1600	2500	1600	38.05	13.96	52.01
	1600	2500	—	37.26	8.92	46.18
	1200	1900	1200	38.21	11.81	50.02
	1200	1900	—	37.94	9.99	38.93

Table 5. *Cont.*

Permeability ($\times 10^{-3}\mu m^2$)	Concentration (mg/L)	Molecular Weight ($\times 10^4$)		Oil Recovery (%)		
		Before Shearing	After Shearing	Water Flooding	ASP Flooding	Total Oil Recovery
200	1600	2500	1600	40.18	15.07	55.25
	1600	2500	—	38.79	9.16	47.95
	1200	1900	1200	40.01	13.08	53.09
	1200	1900	—	38.97	10.23	49.20
600	1600	2500	1600	43.19	17.51	60.70
	1600	2500	—	40.22	9.72	49.94
	1200	1900	1200	42.63	14.98	57.61
	1200	1900	—	39.78	11.21	50.99

Based on the above experimental analysis, the matching relationship between the molecular weight and permeability of the ASP solution is obtained from two aspects: the chemical flooding oil recovery and the maximum injection pressure:

(1) For cores with a permeability of $50 \times 10^{-3}\mu m^2$, non-sheared ASP solution with a molecular weight of 800×10^4 and sheared ASP solution with a molecular weight of 800×10^4 and a low concentration of 1000 mg/L (molecular weight 1900×10^4 or 1200×10^4 before shearing) should be selected for oil displacement.

(2) For cores with a permeability of 100×10^{-3} μm^2, non-sheared ASP solution with a molecular weight of 1200×10^4 and sheared ASP solution with a molecular weight of 1600×10^4 and concentration of 1200 mg/L (molecular weight 2500×10^4 or 1900×10^4 before shearing) can be selected for oil displacement.

(3) For cores with a permeability of 200×10^{-3} μm^2, non-sheared ASP solution with a molecular weight of 1200×10^4 and sheared ASP solution with a molecular weight of 1600×10^4 and concentration of 1600 mg/L (molecular weight of 2500×10^4 or 1900×10^4 before shearing) can be selected for oil displacement.

(4) For cores with a permeability of $600 \times 10^{-3}\mu m^2$, non-sheared ASP solution with a molecular weight of 1600×10^4 and concentration of 1600 mg/L can be selected for oil displacement, i.e., oil displacement is not carried out by using a partial quality tool.

4. Conclusions

According to laboratory experiments, the injection capacity and oil displacement effect of ASP solution in cores with different permeabilities before and after the use of a partial quality tool were studied, and the following conclusions were obtained:

1. The highest injection pressure of the high molecular weight ASP solution in the low permeability oil layer is large, the injection capacity is poor, the matching degree with the oil layer is poor, and the oil displacement effect is low.

2. The partial quality tool can change the spatial grid structures of molecules through different degrees of shearing, and the control range of the molecular weight of high molecular weight ASP solution can reach 7.26–54.16%.

3. Compared with the low and medium molecular weight ASP solutions without the shearing action of the partial quality tool, the low and medium molecular weight ASP solutions obtained by the high molecular weight ASP solution with the shearing action of the partial quality tool have a smaller maximum injection pressure and a stronger injection capacity in low permeability cores but a poorer oil recovery.

4. After the high molecular weight ASP solution is sheared by the partial quality tool, the highest pressure drops, with the maximum drop rate reaching 61.7%, and the injection capacity in low permeability cores is improved, with the degree of oil recovery increasing to a maximum of 80.1%.

5. For heterogeneous oil layers, the use of a partial quality tool can improve the oil displacement effect of low permeability oil layers and enhance the overall oil recovery.

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