

Research Article

Study on Compatibility of Polymer Hydrodynamic Size and Pore Throat Size for Honggang Reservoir

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Long core flow experiment was conducted to study problems like excessive injection pressure and effective lag of oil wells during the polymer flooding in Honggang reservoir in Jilin oilfield. According to the changes in viscosity and hydrodynamic dimensions before and after polymer solution was injected into porous media, the compatibility of polymer hydrodynamic dimension and the pore throat size was studied in this experiment. On the basis of the median of radius R of pore throats in rocks with different permeability, dynamic light scattering method (DLS) was adopted to measure the hydrodynamic size R_h of polymer solution with different molecular weights. The results state that three kinds of 1500 mg/L concentration polymer solution with 2000×10^4 , 1500×10^4 , and 1000×10^4 molecular weight matched well with the pore throat in rocks with permeability of 300 mD, 180 mD, and 75 mD in sequence. In this case, the ratios of core pore throat radius median to the size of polymer molecular clew R/R_h are 6.16, 5.74, and 6.04. For Honggang oil reservoir in Jilin, when that ratio ranges from 5.5 to 6.0, the compatibility of polymer and the pore structure will be relatively better.

1. Introduction

Polymer flooding can improve the water-oil mobility ratio in the oil layer, effectively enlarge the swept volume, and be capable of enhancing oil recovery up to 10%, and this technology has already been carried out in Daqing oilfield [1–4]. The polymers used for flooding (partially hydrolyzed polyacrylamide (HPAM)) are trackless coils consisting of one or more twined molecular chains in the solution [5], and the clew size is affected by many factors, such as the relative molecular weight of polymer, polymer concentration, and the ionic concentration of the sample water [6–8]. Theoretically, for some reservoirs, under a certain concentration, with increasing relative molecular weight of the polymer, the viscosity improves, the hydrodynamic size increases, and the control ability over fluidity gets stronger [9, 10]. However, during the real injection process, the polymer used as oil-displacing agent will be naturally selected by the pore throat

sizes as flowing through porous medium instead of entering the pores and throats in the porous mediums completely [11]. When the hydrodynamic size is way larger than the throat size of rock and under normal injection pressure, the polymer molecules will accumulate in the pipeline or at the core entrance and only a small amount of relative small molecular clews can enter the core [12]. Even though under some external forces, molecular clews with larger size may manage to enter the cores, the molecular structure will be damaged, and the displacement will be ineffective [13]; in addition, the migration distances for the polymer molecules entering the cores will be relatively short, which also make it difficult to generate effective displacement ability. Taking effect inconspicuously in oil wells is a typical issue at the mine field, and some objective intervals will also have some issues like pressure skyrocketing and failing to inhale, both of which will weaken the injectability. So how to improve the effect of polymer flooding and further enlarge the swept volume so as

TABLE 1: Water quality parameters of the on-site injection water from Honggang oilfield in Jilin.

Ion	K ⁺ , Na ⁺	Mg ²⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
Concentration (mg/L)	162.5	36.7	87.8	127.6	164.6	454.2

to enhance the reserve utilization degree has been a research hotspot [14]. Therefore, it is of paramount importance for formulating the scheme and developing polymer flooding technology to study the matching relation between polymer and reservoirs with different permeability through analyzing the compatibility of hydrodynamic size and pore throat size. Polymer solution flooding experiment was conducted with 10 cm long core by predecessors [11], and the compatibility of polymer hydrodynamic dimension and the pore throat size was studied just according to the core inlet pressure. However, long cores were not used to test pressure distribution in the core yet. Besides, the changes of viscosity and the molecular size of the effluent were not tested in other experiments.

In this paper, long cores with different permeability and 4 kinds of polymer with different molecular weight in X Block of Honggang reservoir located in Jilin oilfield were taken as the samples. The core flow test was used to detect the propagation rule of pressure during polymer injection process and judge the migration features of polymer. The changes in the viscosity of polymer solution and the clew sizes pre- and postcore injection were tested, so as to study the compatibility of hydrodynamic size and pore throat size.

2. Experiment

2.1. Experimental Materials and Apparatus. The polymers utilized were 4 kinds of HPAM named after p1, p2, p3, and p4 in this paper with different relative molecular weights of 800×10^4 , 1500×10^4 , 2000×10^4 , and 2500×10^4 , respectively, and the effective solid content was 80%. The water used for preparing liquid was taken from the injection water on site of Honggang reservoir in Jilin oilfield with 1033.4 mg/L salinity. The ion composition and concentration are exhibited in Table 1. Water for preparing the fluid was prepared by filtering sample water on 0.22 μm membranes and storing. The formation fracture pressure of target Block X is 52 MPa.

The homogeneous long core used in the experiment was entirely pressed by outcrops with different radiuses. First, the outcrops were crushed into particles, and then particles were pressed into the cylindrical core with inorganic cementing agent under certain pressure. Their pore sizes are close to each other according to the mercury injection experiment. Compared with the quartz sand used for making normal core, the particle shape and surface properties of the outcrop sand are more similar to a real core because they have the same mineral composition. The core had 2.5 cm radius and 100 cm length. According to the reservoir permeability distribution of X Block in Jilin Honggang oilfield, representative cores were chosen with 300 mD, 180 mD, and 75 mD air permeability, 148 mD, 87 mD, and 30 mD water permeability, and 23.4%, 22.11%, and 20.32% porosity, and their pore

throat radius medians were 3.14 μm , 2.13 μm , and 1.51 μm , respectively, according to the mercury injection test.

Main experimental facilities are as follows: self-designed long core physical simulation equipment (Figure 1)—including a long core holding unit with surveying points (the surveying points in the middle divided the model into two equal parts), incubator, pressure sensor with high precision, data acquisition system, ISCO pump with constant velocity and pressure, HAAKE Rotational Rheometer, and microburette.

2.2. Experimental Method. Prepare the polymers with different molecular weights into a mother solution with 5000 mg/L concentration by using the on-site injection water and leave it to stand for 4 h and then dilute it into 1500 mg/L target solution. After that, shift 5 of warring blender shear apparatus was used to simulate the shearing action of the shot hole for 10 s before storage.

2.2.1. Determination of Viscosity. The viscosities of the polymer solutions before and after injection were determined at a shear rate of 7.34 s^{-1} with HAAKE Rotational Rheometer-6000 at 55°C.

2.2.2. Determination of Polymer Molecular Clew Size. American Brookhaven BI-200SM wide angle dynamic/static light scattering with 523 nm wavelength was adopted, and the concentration of polymer solution was 100 mg/L. DLS method has wide measurement range, high measurement speed, and less sample amount.

2.2.3. Mobility Test

- (1) Vacuumize the core and saturate the formation water, measure the core permeability by water, and calculate the porosity.
- (2) Conduct water flooding and polymer flooding under 55°C, record the injection pressure, collect the produced liquid, and measure relevant parameters.
- (3) Conduct water flooding under 55°C for a second time, record the injection pressure, and measure relevant parameters.

Referring to the responding time of polymer flooding in Daqing oilfield, the linear velocity of effective flow for the fluid flowing in the stratum was figured out to be 1 m/d. Therefore, 3–5 PV polymer solution was injected continuously with an injection flow of 0.1 mL/min until a stabilized situation was achieved.

3. Experimental Results and Discussion

3.1. Injection Characters of Polymer Solution. The propagation performance of polymers propagating in the porous medium was evaluated primarily, that is to say, whether there is retention phenomenon during the injection process. The propagation rules of pressure were evaluated principally. If

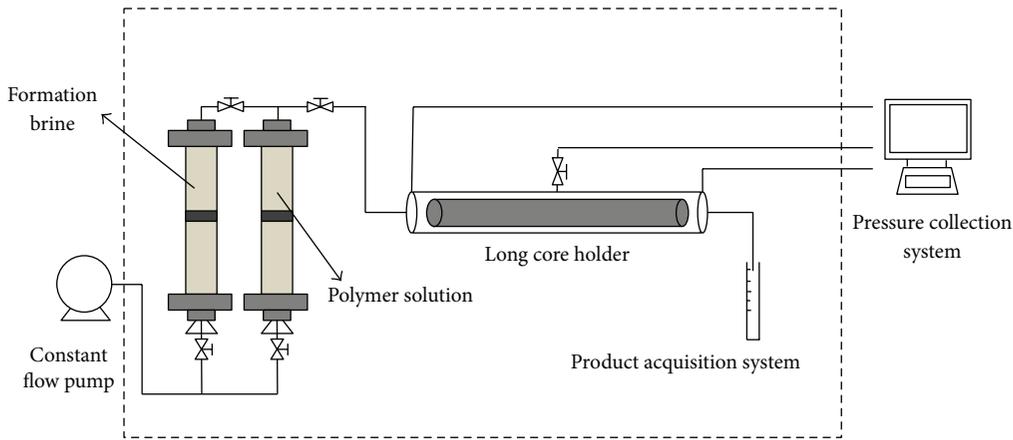


FIGURE 1: Flow chart of injection experiment.

the polymer solution has preferable propagation performance in the porous medium, then no block will emerge and the pressure will drop equally throughout homogeneous cores. Moreover, the resistance coefficients of the front half and latter half of the core will be close. Resistance coefficient (RF) is the ratio between water and polymer solution mobility:

$$RF = \frac{\lambda_w}{\lambda_p} = \frac{K_w/\mu_w}{K_p/\mu_p}. \quad (1)$$

In the equation, RF is the resistance coefficient (a nondimensional parameter); λ_w is the water mobility; λ_p is the polymer solution mobility; K_w is the water phase permeability, in mD; K_p is the polymer solution permeability, in mD; μ_w is the viscosity of water, in mPa·s; μ_p is the viscosity of polymer solution, in mPa·s.

When the hydrodynamic size of the polymer is larger than the throat size of rock, the polymer molecules will accumulate at the core entrance or travel short distances in the core, so the pressure and resistance coefficients in the front and back long core sections are very different. When the hydrodynamic size of the polymer has a very good compatibility with the throat size of rock, the polymer molecules will travel smoothly in the core and are distributed evenly throughout the core. So the pressure and resistance coefficients in the front and back long core sections are much closed. Figure 2 shows the pressure variation with the change in injection volume when 4 kinds of polymer solutions were injected into 3 kinds of cores with different permeability. A surveying point on the experimental model divided the model into two parts (PX-1 and PX-2 are the pressure at the core entrance and the middle part, resp.). When the pressure on the surveying points goes up, it indicates that the polymer solution has migrated to this part. During the process of chemical agent injection, it is the pressure around the entrance that rose first, and the pressure at the middle increased along with the chemical agent migration. Four kinds of polymer solution with different molecular weights were injected into cores with 300 mD, 180 mD, and 75 mD permeability, and their variation tendencies are shown in Figures 2(a), 2(b), and 2(c), respectively.

Figure 2(a) shows the pressure variation with injection volume by injecting solutions prepared by p2, p3, and p4 polymers into a core with 300 mD permeability. As shown in the figure, when a small amount of p4 polymer solution (25 million molecular weight) was injected, the pressure at the entrance surged while pressure in the middle showed no obvious variation, the differential pressure between the front and back sections was 7.12 MPa, and the resistance coefficients of the two sections were 389.3 and 3.7, respectively. This meant that the polymer solution mainly accumulated at the core entrance, and only when the injection volume reached 2.0 PV, pressure in the middle would finally increase slightly. The injected polymer molecules also accumulated on the front part of the core and failed to achieve remote migration. The phenomenon in return explained on-site injection well pressure build up and injection failure issues at the oilfield. Pressure unable to delivery efficiently will lead to injection pressure build up or even fracture at the stratum. Moreover, during the injection process of p4 solution, the pressure was always changing, which meant that the polymer molecular clews were oversized and mismatched with the size of formation pores. The displacement agent of p3 solution was prepared by polymers with 20 million molecular weight, the pressure increased gradually from the core entrance (P3-1) to the middle part (P3-2) with a steady rising velocity, the differential pressure between the entrance and the middle part was 2.13 MPa, and the resistance coefficients of the front and back sections were 106.5 and 105, respectively. This reflected the steady migration process of chemical agent in the model and preferable compatibility of polymer molecular clew size and the pore size. During the process of p2 solution injection, the pressure increased gradually from the core exit (P2-1) to the entrance (P2-2) with steady rising velocity, which further reflects the stable migration process of chemical slug in the model. However, due to the low injection pressure in the injection system, the differential pressure was 1.03 MPa, and the resistance coefficients of the front and back parts were 53 and 46, respectively. The excessive velocity of the injection system in the large pores led to a failure of controlling the fluidity, which means that polymer molecular clew was undersized and mismatched with the pore size.

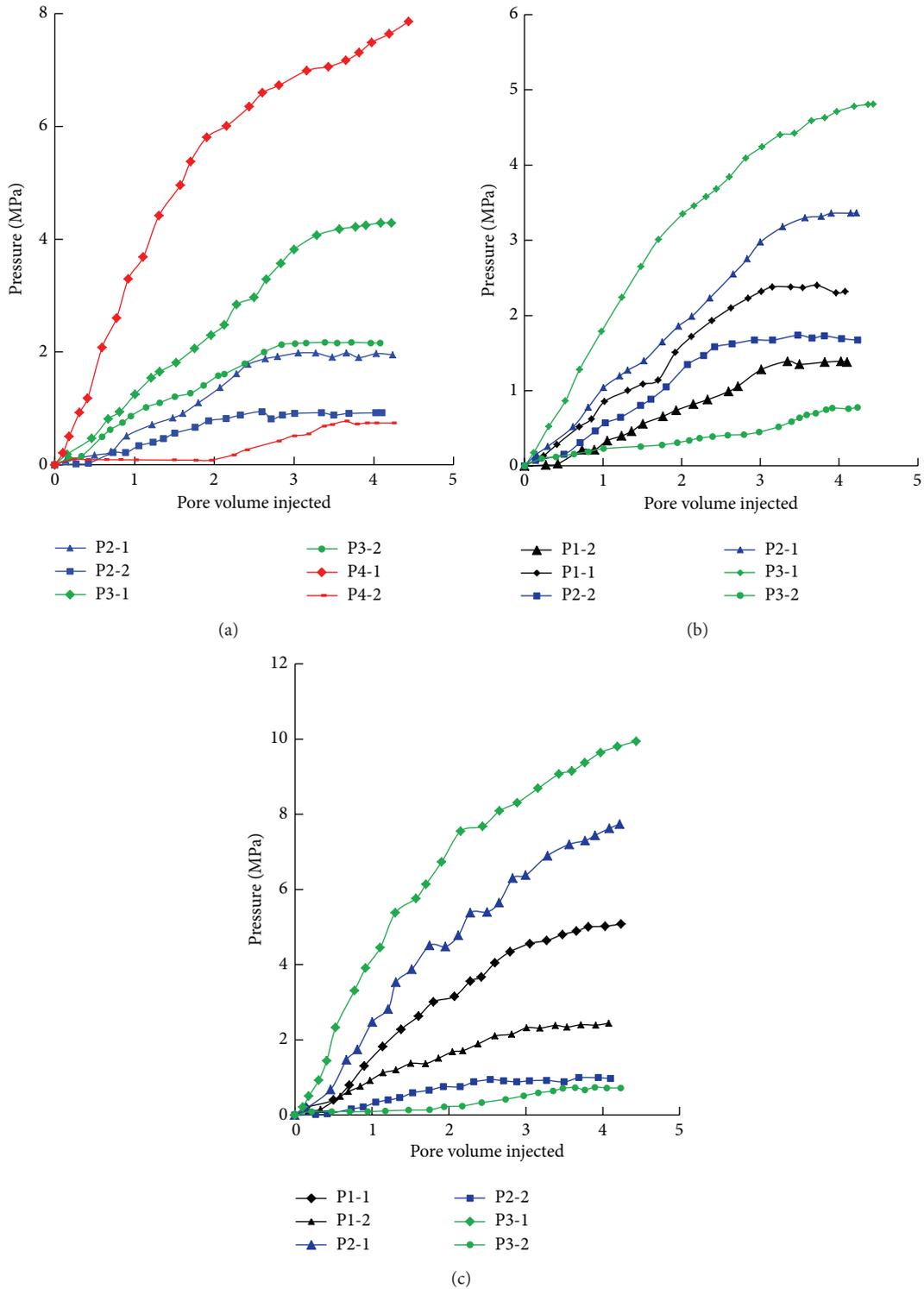


FIGURE 2: Injection pressures variation with injection volume of different polymer solutions ((a) Kg: 300 mD; (b) Kg: 180 mD; (c) Kg: 75 mD).

Figure 2(b) is a diagram of the pressure variation with the injection volume as injecting polymers p1, p2, and p3 into a core with 180 mD permeability. The pressure of solution prepared by p3 increased at the entrance (P3-1), while there was no change in the middle (P3-2), the differential

pressure was 3.3 MPa, and the resistance coefficients of the front and back sections were 201 and 39, respectively. This means that the polymer solution mainly accumulated at the core entrance, and the oversized polymer molecular clew in the solution prepared by p3 mismatched with the pore

TABLE 2: Viscosity and its loss rate in the produced liquid with 4 kinds.

Kg, mD	p1		p2		p3		p4	
	Viscosity, mPa·s	Loss rate, %						
300	12.36	4.31	21.13	5.95	41.95	8.26	51.94	31.12
180	11.96	7.45	20.27	9.77	33.23	27.32	34.89	53.73
75	11.77	9.16	13.76	38.77	22.85	50.03	21.48	71.51

The viscosities of the four kinds of polymer solution with 1500 mg/L concentration were 75.40 mPa·s, 45.73 mPa·s, 22.47 mPa·s, and 12.92 mPa·s in sequence before injection.

TABLE 3: Changes in the hydrodynamic dimensions of the produced liquid from polymer solution.

Kg mD	p1		p2		p3		p4	
	$R_h, \mu\text{m}$	Loss rate, %						
300	0.24	4.0	0.34	5.6	0.46	9.8	0.52	18.8
180	0.23	8.0	0.32	11.1	0.42	17.6	0.45	29.7
75	0.22	12.0	0.28	22.2	0.34	33.3	0.36	43.8

The hydrodynamic dimensions of 4 kinds of polymer solutions p1, p2, p3, and p4 with 100 mg/L concentration are 0.25 μm , 0.36 μm , 0.51 μm , and 0.64 μm , respectively (the order was ranked by their molecular weights).

size in a stratum with 180 mD permeability. The pressure variation tendency of the solution prepared by p2 shows was approximately linear increase from the core entrance to the middle part, the differential pressure between the surveying points at the entrance and in the middle was 1.69 MPa, and the resistance coefficients of the front and back sections were 84.5 and 83, respectively. This means that the chemical agent migrated steadily in the core and implies a good compatibility of polymer molecular clew size and pore size. Figure 2(c) shows the pressure variation with the injection volume as p1, p2, and p3 polymers were injected into a core with 75 mD permeability. The pressure variation of solution prepared by p1 increased uniformly from the core entrance to the middle part, the differential pressure between the entrance and the middle part was 2.56 MPa, and the resistance coefficients of the front and back sections were 128 and 122, respectively, which illustrated that the polymer molecular clew size matched well with the pore size.

3.2. Changes in Polymer Solution Viscosity. Table 2 shows the viscosity changes in produced liquid after 4 kinds of polymer solution were injected into 3 kinds of cores with different permeability.

The polymer viscosity loss was mainly due to the shearing and absorption effect, and several conclusions are suggested by the data: for cores with the same permeability, the viscosity loss rate of the produced liquid increased with the polymer molecular weight. This means that with increasing molecular weight, the length of polymer molecular chain after hydration increased and the polymer became easier to be broken under stress during the migration process in the pores, leading to an increase in the viscosity loss rate. Under the same polymer molecular weight conditions, smaller core permeability means smaller pore size, more complex structure, which will result in stronger shearing effect on polymer, larger specific surface area of core, more severe absorption effect on

polymers, and, as a consequence, a serious viscosity loss of the polymer solution.

Combined with the flow test in the cores and conducting some further analysis, p1, p2, and p3 matched well with the cores with 300 mD, 180 mD, and 75 mD permeability, and these three kinds of polymer solutions had little viscosity loss rate in the cores with corresponding permeability and stable pressure. To further verify their matching relations, micro-analysis is required to measure changes in hydrodynamic dimensions.

3.3. Changes in the Polymer Hydrodynamic Dimensions. Four kinds of polymer solution with different molecular weight and 1500 mg/L concentration were injected into cores with 300 mD, 180 mD, and 75 mD permeability at 0.1 mL/min velocity until the pressure was stable, after which the hydrodynamic dimensions of produced liquid at the exit were measured, and both the polymer solution and produced liquid were diluted to 100 mg/L. The polymer molecular clew sizes and light scattering distribution results are reported in Table 3.

As shown in Figure 3, the average hydrodynamic dimension R_h of the polymer solution with 800×10^4 , 1500×10^4 , 2000×10^4 , and 2500×10^4 molecular weights before injection were 0.25 μm , 0.36 μm , 0.51 μm , and 0.64 μm , respectively, and the peak values are relatively concentrated. After flowing over the core, the R_h of polymer solution decreased, and, for the same core permeability conditions, a larger polymer molecular weight means greater drop in hydrodynamic dimension; for solutions with the same polymer molecular weight, lower permeability means greater drop degree of the hydrodynamic dimension, which is mainly due to the low permeability and small pore size. This makes a molecular clew with relatively larger size unable to pass through the pores with its molecular structure undamaged. After passing through cores with different permeability, the peak value of polymer R_h moved towards left and the proportion of

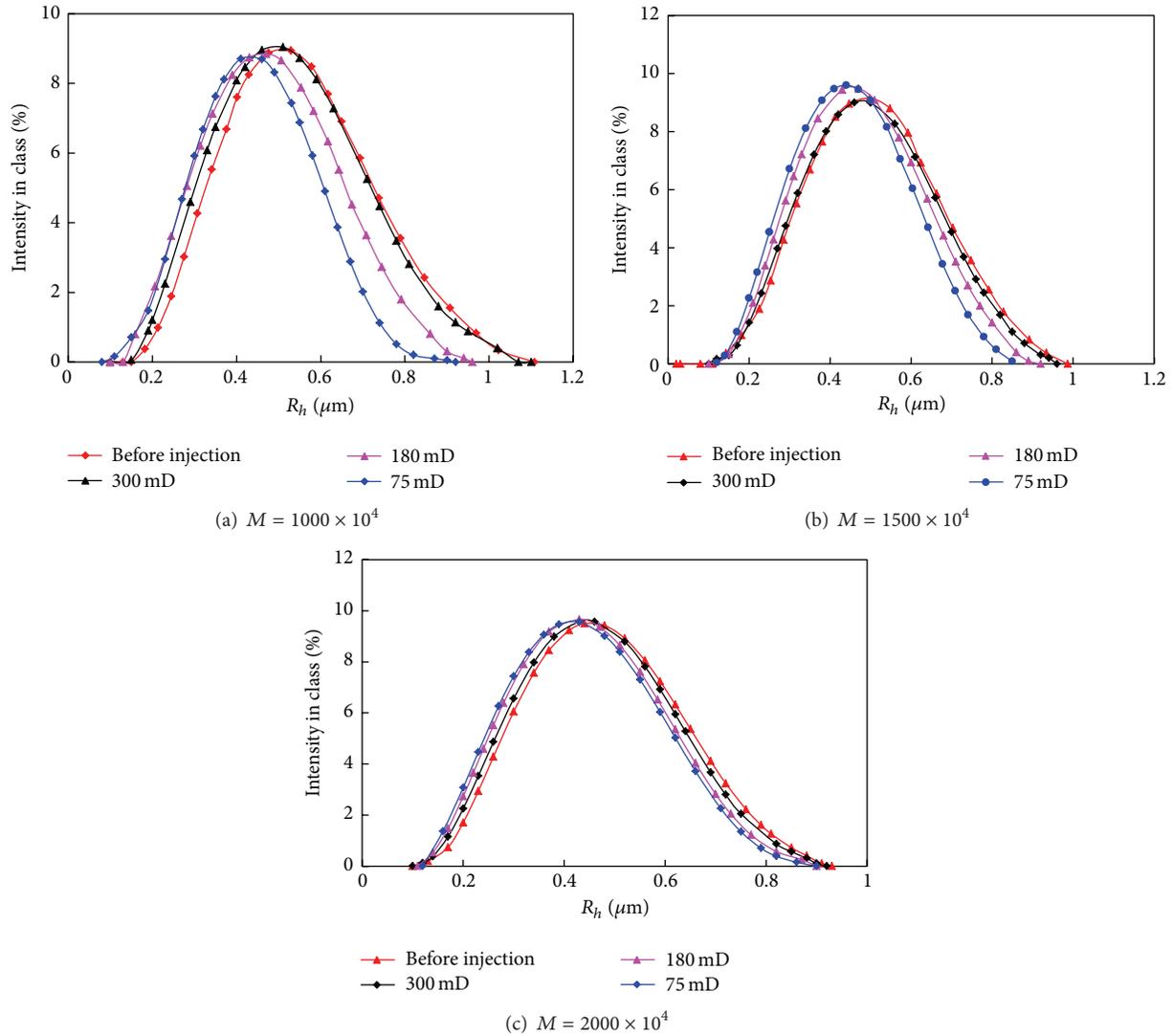


FIGURE 3: R_h distribution of polymer solution with different relative molecular mass before and after injection of different permeability cores.

polymers with relatively smaller hydrodynamic dimensions increased. In contrast, the proportion of polymers with relatively larger R_h decreased and the phenomenon can be explained in this way: when the polymers passed through the pores and throats in the core, the quantity of polymer with larger R_h decreased with decreasing core permeability, and that was consistent with the conclusion about viscosity loss rate.

3.4. Compatibility of Polymer Molecular Clew Size and Pore Throat Size. As different researchers defined differently the pore radius, the water used for preparing polymer solution had different salinity, and, for different reservoir conditions, the specific values R/R_h for representative polymer and core compatibility were hard to determine.

In this paper, the reservoir conditions in Honggang oilfield were used, and the polymer hydrodynamic size and the pore throat radius were unified at their average values. Table 4 shows the relevant data.

TABLE 4: Calculation results of the specific value of pore throat radius median to average hydrodynamic dimension.

Polymer parameters		Core parameters		R/R_h
M	$R_h/\mu\text{m}$	Kg/mD	$R/\mu\text{m}$	
2000×10^4	0.51	300	3.14	6.16
1500×10^4	0.38	180	2.18	5.74
1000×10^4	0.25	75	1.51	6.04

To avoid polymer retention in the pore throats in the stratum of Honggang reservoir, the core permeability, polymer concentration, relative molecular weight, and the chemical composition of the solvent water were taken into consideration. Generally, R/R_h ranges from 5.5 to 6.0. For stratum with 300 mD, 180 mD, and 75 mD permeability, polymers with relative molecular weight lower than 2000×10^4 , 1500×10^4 , and 1000×10^4 are recommended, and if the shearing and degradation effect during preparation and injection processes

are taken into consideration, the relative molecular weights of polymers can still be increased modestly.

4. Conclusions

- (1) When the polymer solution was injected into cores with different permeability, the injection pressure had varying degrees of increase. Three kinds of polymers with 800×10^4 , 1500×10^4 , and 2000×10^4 molecular weights matched well with the pore throats in cores with permeability of 300 mD, 180 mD, and 75 mD, respectively. They showed preferable injectability and no block at the injection end and propagated uniformly in the cores.
- (2) For Honggang reservoir in Jilin oilfield, when the specific value R/R_h (pore throat radius median/polymer clew size) is among 5.5–6.0, the matching relation between polymer and the pore structure of cores is preferable and can better suit the pore throat structure in the reservoirs.
- (3) During the practical application of polymer flooding at Honggang oilfield in Jilin, for stratum with 300 mD, 180 mD, and 75 mD permeability, polymers with 2000×10^4 , 1500×10^4 , and 1000×10^4 molecular weights were recommended, and if the shearing and degradation effect during preparation and injection processes are taken into consideration, the relative molecular weights of polymers can still be increased modestly.

Conflict of Interests

The authors declare no conflicts of interests regarding the publication of this paper.

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