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Research on matching mechanism between polymer microspheres with different storage modulus and pore throats in the reservoir

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ABSTRACT

Polymer microsphere profile control technology has been a promising new profile control technology in heterogeneous reservoirs. The matching between polymer microsphere and pore throat of the reservoirs is crucial for profile control treatment. In this paper, the matching mechanism between polymer microsphere and pore throat had been systematically studied by sand pack models and micro models. The optical microscope and laser particle size analyzer were used to analyze the morphology and particle size of polymer microspheres before and after injection. The matching factor was proposed to evaluate the compatibility. The long sand pack model was used to evaluate the migration rule of polymer microspheres. Three modes including the migration mode, blockage mode and seepage mode were concluded and five passing through patterns, which were deformable passing through, partition passing through, blockage, adhesion and direct passing through, were observed. The specific corresponding statistical data of matching factors and passing through patterns in different storage modulus was established. The long sand pack displacement experiment showed that polymer microspheres could migrate into the deep reservoir. The comprehensive correlation equation $p_{in} = 3.3072 \times 10^{-7} G'^{2.6492} R^{2.3882 G'^{-0.0568}}$ was derived according to the laboratory physical simulation data and the stable injection pressure of polymer microsphere with different storage modulus in different matching factors was predicted. This research will provide theoretical support for the further EOR research and field application of polymer microspheres profile control system.

1. Introduction

Water is usually injected into reservoirs as a secondary recovery method to maintain the reservoir pressure and displace the oil. However, with the development of mature oilfields, the phenomenon of water breakthrough among oil wells and water wells is more and more serious. In addition, the injected water is not effective for oil displacement. Thus, there is still a large amount of remaining oil in the reservoir. As the number of newly discovered reservoirs decreases, it is of utmost importance to improve the oil recovery of mature oilfields. According to the previous reports, reservoir heterogeneity is one of the most important factors for low oil recovery and water breakthrough [1,2]. Reservoirs with induced fractures or high permeability channels, commonly called thief zones or streaks due to extensive water flooding, are quite common in the mature reservoirs. Many methods, including polymer flooding, alkaline-surfactant-polymer flooding, foam flooding, gel treatments and etc., have been applied to mitigate water breakthrough and to improve oil recovery.

In recent years, gel treatment has proven to be a cost-effective method for conformance control [3–8]. Although in-situ polyacrylamide polymer gels are economically attractive, they have some inherent negative effects on treatment of wells that are brought in by formation temperature, salinity, shearing, adsorption, diluted formation water, chromatographic separation effect or other environmental factors. Considering the negative effects listed above, preformed gels were proposed in the application of conformance control and improve oil recovery. In the early 21st century, a new chemical agent called polymer microsphere was proposed and has attracted extensive concern of scholars [9–11]. Some pilot tests have been performed in Shengli, Jidong, Dagang Oilfield in China and Canada and a good effect of water control and enhanced oil recovery was obtained [12–16]. The polymer microspheres used in petroleum engineering were prepared by inverse phase polymerization and particle size ranged from several nanometer to hundreds of micrometers based on pore characteristics of the target layer in reservoir conditions. Polymer microsphere is a viscoelastic plugging agent with 3-D structure, which can absorb much more water as compared to its own mass, ranging from several to hundreds of times and it is hard to release the absorbed liquids even under high pressure [17–19]. However, except for so many advantages as it has, there are still some problems in the practical application in oilfields.

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One of the problems is the low success rate of profile control due to the poor matching between polymer microspheres and pore throat. In the field test, polymer microspheres were used blindly because of the lack of accurate matching principles. Thus the matching relationship will directly influence the success or failure of profile control treatment. If the matching relationship was too poor, the polymer microspheres could not inject into the deep reservoir and fail to play the role of deep profile control agent. Therefore, it is necessary to investigate the matching mechanism of polymer microspheres and pore throat in the reservoir. Currently, the relation of particle size of polymer microspheres and diameter of pore throat was used to evaluate the matching relationship between polymer microspheres and reservoir by means of core flooding and sand pack flooding experiments. Pritcheet J. et al. investigated the injection and migration properties of polymer microspheres [20]. The results showed that the suitable range of matching relationship was that the initial particle size of polymer microspheres was smaller than the one tenth of diameter of pore throat. The results were different from the research of the other scholars. Lin R. L. et al. established the simplified mechanical model and calculated the critical particle size that polymer microspheres passing through the pore throat [21]. They investigated that the ratio of average particle size and the critical particle size was 1.26 when the storage modulus of 100 Pa, limit stress of 30 Pa, Poisson's ratio of 0.3. Wang T. et al. investigated the plugging property of polymer microspheres [22]. The results showed that the profile control effect was best when the ratio of particle size of microsphere r and pore throat diameter R was 1. Also the plugging rate results indicated that the plugging rate increased from 25% to 50% when the ratio of particle size of microsphere r and pore throat diameter R changed from 0.167 to 0.592. Further in-depth research showed that it was bridge plugging with two microspheres when $0.46R < r < R$, bridge plugging with three microspheres when r equals to $0.46R$, and bridge plugging with four microspheres when r equals to $0.292R$. Lei G.L. et al. researched the effect of injection concentration and injection rate of polymer microspheres on plugging rate [23]. They indicated that the plugging rate decreased with the increase of injection rate and the plugging rate remained constant after the injection rate greater than 5 m/d. It was also observed that the plugging rate of polymer microspheres increased with the increase of injection concentration. Almohsin et al. investigated the injection and plugging property of nano polymer microspheres in porous medium by use of sand pack model [24]. They indicated that the range of permeability that polymer microspheres with particle size of 100–285 nm that could migrate was $143\text{–}555 \times 10^{-3}\ \mu m^2$. From these matching research results above, the matching value between polymer microspheres and pore throat was bigger than the matching value between inorganic particles and pore throat.

Despite of the experimental work to evaluate the matching relationship of polymer microspheres and porous medium, very few studies have been conducted to evaluate the matching mechanism considering the storage modulus of polymer microspheres, except for the particle size of polymer microspheres and diameter of pore throat. The storage modulus determined the deformability of polymer microspheres in the porous medium and affected the profile control effect.

In the present work, the matching mechanism between polymer microsphere and pore throat had been systematically studied by use of sand pack models and micro models. The storage modulus, particle size of polymer microspheres and diameter of pore throat were considered during the research of matching mechanism. Three modes and five passing through patterns of polymer microspheres in pore throats were concluded. The specific corresponding statistical data of matching factors and passing through patterns in different storage modulus was established. Moreover, we derived the quantitative comprehensive correlation among stable injection pressure, storage modulus and matching factor according to the laboratory physical simulation data. From this research, we offer the principles to choose the appropriate particle size and storage modulus polymer microspheres in the field test according to the reservoir condition. This research will provide theoretical support for the further EOR research and field application of polymer microspheres profile control system.

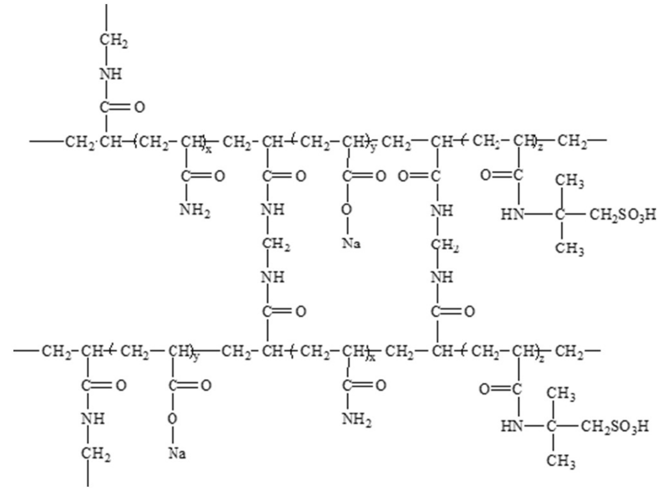

Fig. 1. Molecular structural formula of polymer microsphere used in this paper.

2. Experimental section

2.1. Materials

Five polymer microspheres with different storage modulus (G'): LEM-1 of 23.6 Pa, LEM-2 of 32.5 Pa, HEM-1 of 121 Pa, HEM-2 of 466 Pa, HEM-3 of 715 Pa. The molecular structural formula of polymer microspheres used in this paper was shown in Fig. 1. The storage modulus of polymer microspheres was controlled by adjusting the crosslinking density of bulk gel of polymer microspheres. The storage modulus measurement method of polymer microspheres was to measure the storage modulus of bulk gel of polymer microspheres using mechanical rheometer [25]. Hydrolyzed polyacryamide (HPAM, relative molecular mass 27.4×10^6, degree of hydrolysis 23.8%) was supplied by Dagang Oilfield (China), silica sand was purchased from the market. The oil used in this study was Dagang Oilfield (China) dehydrated crude oil. The composition of simulated formation water used in this paper was shown in Table 1.

2.2. Microscopic characterization of polymer microspheres

XSJ-2 optical microscope (Chongqing Optical Instrument Co., Ltd., China) was used to observe the morphology of low elastic microspheres.

A Rize2006 laser particle size analyzer (Jinan Runzhi Technology Co., Ltd., China) was used to analyze the particle size. In the particle size distribution curves, D_{50} was introduced to express the average particle size of microspheres before and after swelling. D_{50} is the particle size of cumulative distribution curve on probability of 50%.

2.3. Compatibility evaluation method between polymer microsphere and porous medium

Polymer microspheres mainly migrated in the high permeability channels or fractures, thus the sand pack models filled with quartz

Table 1
Dagang oilfield simulated formation water.

Composition	Na^+/K^+	Ca^{2+}	Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Total
Concentration, mg/L	2043	39	36	1337	135	3126	10	6726