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Visual investigation on oil recovery enhancement via polymer flooding in heterogeneous reservoir

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ABSTRACT

As an alternative, polymer flooding has been widely promoted and tested in the heterogeneous reservoir. In our earlier studies, we have recognized that oil recovery increases with the viscosity of the polymer as the displaced phase by observing the Hele-Shaw model.

Using visualization techniques, we explore the effects of water flooding and polymer flooding on fluid flow in a vertical heterogeneous reservoir filled with porous media. Based on macro-micro experimental image recognition, this study obtains the characteristics of the saturation distribution and production performance on water flooding and polymer flooding. The performance evaluation of planar sweep efficiency and vertical flow profile adjustment of polymer flooding has been systematically investigated to clarify the mechanism of enhanced oil recovery by polymer flooding. Compared with primary water flooding, the oil recovery of subsequent water flooding increases demonstrates that polymer flooding achieved better planar sweep performance based on macroscopic images. The work also qualitatively analyzed the changes of various types of residual oil during polymer flooding based on microscopic images.

Through literature and experimental research, we realized that a plethora of factors in polymer flooding may affect the development of drainage zones in heterogeneous reservoirs, including but not limited to polymer-oil mobility ratio, the timing of injection, velocity of injection, and polymer-rock surface adsorption. After optimizing the injected polymer parameters in this study, we tested the percolation condition of polymer in reservoirs with different permeability. The results displayed that the polymer easily entered the high-permeability layer and weakened its fingering phenomenon of preferential flooding channel. By the method of controlling the amount of polymer solution and observed preferential flooding channels interactions to the type of residual oil, we were able to design more comprehensive and appropriate evaluation methods for improving the performance of vertical heterogeneous reservoirs.

Keywords: Visual investigation; Polymer flooding; EOR; Residual oil; Heterogeneous reservoir

NOMENCLATURE

PV	Pore volume injection
f_{hw}	Water cut of the high-permeability layer
f_{mw}	Water cut of the medium-permeability layer
f_{lw}	Water cut of the low-permeability layer
V_{hL}	Percentage of liquid produced in the high-permeability layer
V_{mL}	Percentage of liquid produced in the medium-permeability layer
V_{lL}	Percentage of liquid produced in the low-permeability layer
R_H	Oil recovery of the high-permeability layer
R_M	Oil recovery of the medium-permeability layer
R_L	Oil recovery of the low-permeability layer

1. INTRODUCTION

Heterogeneous reservoirs are widely distributed around the world. It's heterogeneity that reduces swept region during water flooding and other flooding processes in reservoirs, which results in a large amount of residual oil (Jian et al., 2006). The macroscopic distribution of residual oil is formed by the accumulation of residual oil at the microscopic scale, which has a complex formation mechanism. Therefore, some research methods needed to be proposed to study the formation and distribution types of residual oil. Previous studies have discussed that different technique to study the distribution of residual oil. Computer tomography (CT) was quantitatively studied that the micro-occurrence of residual oil in extra-low permeability sandstone (Gu et al., 2019). Nuclear magnetic resonance (NMR) was used to describe the residual oil distribution after water flooding (Wei et al., 2020). Microscopic etching glass modeling experiment and computer image recognition were used to study dynamic residual oil about percolation characteristics in pore-scale (Wang et al., 2017). According to the shape of the residual oil, some researchers divide the residual oil into four types: clusters, columnar, membrane, and blind-end. Some researchers consider that pore-scale heterogeneity is the key factor to control the distribution of microscopic residual oil (Sun et al., 2021; Yue et al., 2018). As an effective method of chemical flooding, polymer flooding has achieved an obvious stimulation effect and huge economic benefits (Wu et al., 2020; Yu et al., 2019).

According to previous studies, there are many proposed mechanisms for polymer flooding to enhance oil recovery in heterogeneous reservoirs. Poor sweep efficiency can be increased by polymer flooding (Adams, 1982; Crespo et al., 2014). Polymer flooding can inhibit the mobility of injected water by increasing the oil-water mobility ratio, which plays an important role in expanding the swept region of the heterogeneous reservoir (Bera et al., 2020; Zhang et al., 2021). Some long chain of water-soluble polymer extends in the formation of water and form the polymer solution with high elasticity, which leads to the increase of water viscosity and oil-water mobility ratio. The polymer has long chains with many polar groups, which attaches to the available polar points on the rock surface (Al-Hajri et al., 2018; Torrealba and Hoteit, 2019). The accumulation of polymer can block preferential flooding channel causes the increase of displacement pressure, which is easy to increase the plane sweep efficiency (Seright et al., 2012).

In a previous study, the traditional invisible model only reflects the alteration of pressure and production, which indirectly reflects the development effect of polymer flooding (Sorbie and Seright, 1992). In the paper, we used the visual sand-pack model to study the processes of water flooding and polymer flooding in heterogeneous reservoirs. Following are the questions which reflect the key points in the paper:

1. What are the characteristics of saturation distribution and production in heterogeneous reservoirs during primary water flooding?

2. How does polymer affect the plane sweep efficiency in heterogeneous reservoirs?

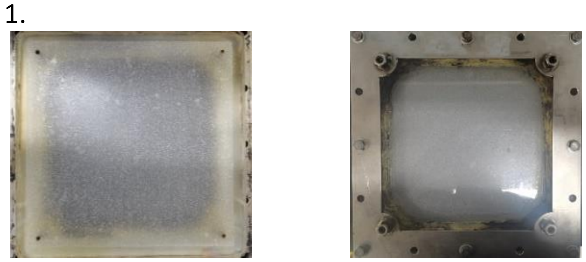
3. Can the polymer adjust the percolation profile in a heterogeneous reservoir?

4. How does polymer reduce the residual oil in the swept region?

2. EXPERIMENT

2.1 Experimental model

The visual filling model is the observation subject in the experiment. The visual filling model consists of two glass plates with a length of 25cm (Wu et al., 2019). The glass beads which simulate the rock skeleton and thermal resistant colloids which simulate the formation cement are the main structure of the visual filling model. In particular, one of the glass plates is equipped with four penetrating holes to simulate the wellbores as shown in Fig 1.



(a) (b)

Fig 1 Structure image of the visual sand-pack model

The three models are filled with glass beads which have three sizes of 20 mesh (830μm), 30 mesh (550μm), and 40 mesh (380μm) to simulate the vertical heterogeneous reservoir. The glass beads are produced by Dongguan Jinying Abrasive Technology Co., Ltd., which have the characteristics of strong pressure resistance and good chemical stability.

2.2 Experimental fluid

The fluid used in the experiment is simulated water, crude oil, and polymer solution. The salinity of the simulated water was measured at 2.86×10^4 mg/L. The crude oil used in the experiment has a viscosity of 60 mPa • s and a density of 952 Kg/m^3 at 55 ℃. The polymer used in the experiment is anionic partially hydrolyzed polypropylene amine, which is produced by Tianjin Zhiyuan Chemical Reagent Co. Ltd. The polymer used in the experiment has a viscosity of 82 mPa • s at 55 ℃ and 60 s^{-1}.

2.3 Experimental apparatus

The experiment apparatus consists of three systems, including a visual model system, fluid displacement system, image and production data acquisition system. Each part of the experimental apparatus is connected as shown in Fig 2.

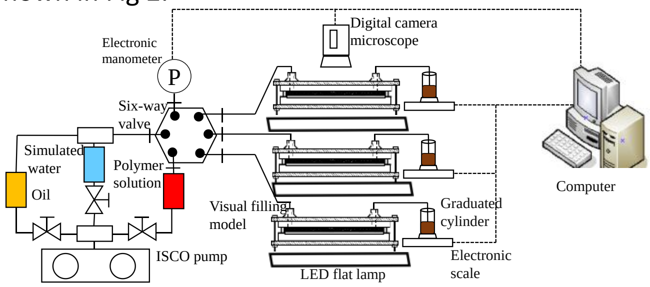
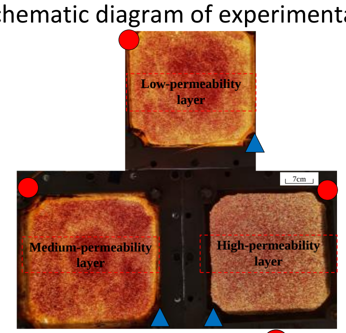


Fig 2 The schematic diagram of experimental apparatus

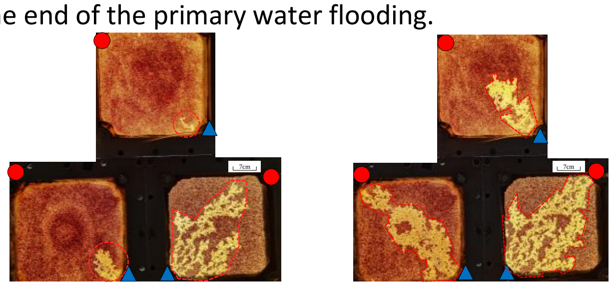


▲ Injection well ● Production well

Fig 3 The initial state of macroscopic saturation

2.4 Results

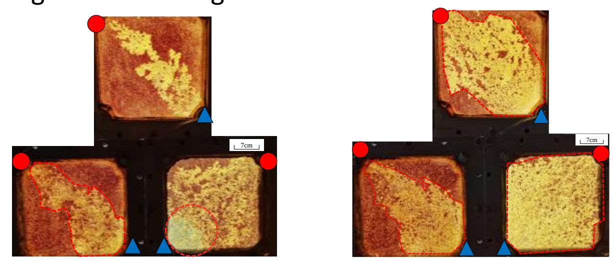
The initial state of macroscopic saturation in the vertical heterogeneous reservoir is shown in Fig 3. The macroscopic saturation alteration of primary water flooding is shown in Fig 4. When a small amount of water entered the heterogeneous reservoir(0.18PV), the water broke through quickly in the high-permeability layer. With the preferential flooding channels formed in the high-permeability and medium-permeability layer, the total water cut increased rapidly, which eventually leads to the end of the primary water flooding.



(a) Primary water flooding (0.18PV) (b) Primary water flooding (0.31PV)

Fig.4 The macroscopic images of primary water flooding

The water firstly enters the high-permeability layer, which is called "water tonguing". Water tonguing causes the waterflood front to appear firstly in the high-permeability layer. Because the viscosity of water is lower than that of crude oil, viscous fingering would occur (Al-Shalabi and Ghosh, 2016; Macminn et al., 2009). Under the synergistic effect of water tonguing and viscous fingering, water forms the preferential flooding channel in the high-permeability layer. After primary water flooding, the preferential flooding channel with small percolation resistance has been formed in the high-permeability layer. The macroscopic saturation alteration of polymer flooding and subsequent water flooding is shown in Fig 5.



(a) Polymer flooding (0.45PV) (b) Subsequent water flooding (1.45PV)

Fig 5 The macroscopic images of polymer flooding

As shown in Fig 6, the sweep efficiency alteration by polymer flooding is statistically analyzed. And the production performance curve of the heterogeneous reservoir is shown in Fig 7.

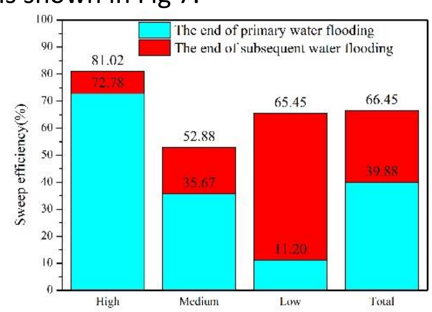
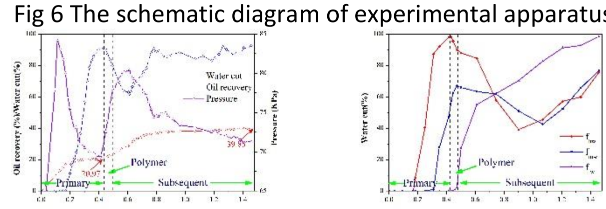
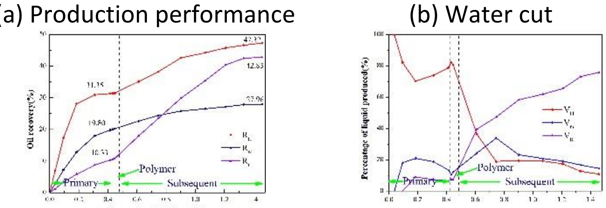


Fig 6 The schematic diagram of experimental apparatus



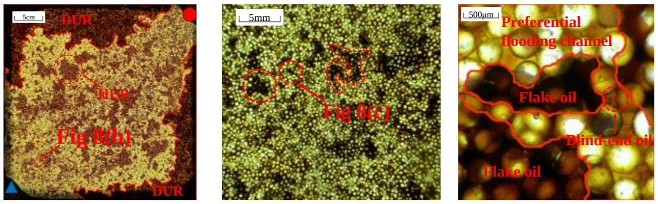
(a) Production performance (b) Water cut



(c) Oil recovery (d) Liquid production

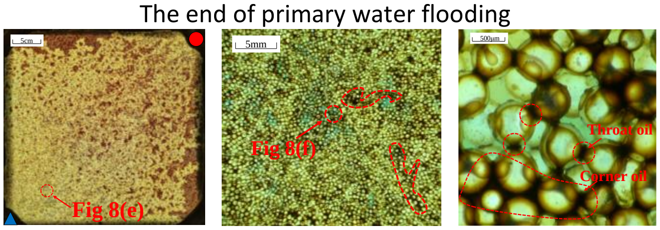
Fig 7 The images of production performance

With the polymer entering the preferential flooding channel in the high-permeability layer, the percolation resistance increases continuously. In the terms of percolation resistance, the polymer enters the medium-permeability layer along the preferential flooding channel after the high-permeability layer exceeds the medium-permeability layer, which increases percolation resistance.



(a) (b) (c)

The end of primary water flooding



(d) (e) (f)

The end of subsequent water flooding

Fig 8 The microscopic analysis of residual oil

After primary water flooding, the layer is divided into the macroscopic swept region and “displacement unswept region” (DUR) which is unaffected by water as shown in Fig 8(a). Furthermore, macroscopic swept region is divided into the preferential flooding channel and “heterogeneous unswept region” (HUR).

After polymer flooding, the subsequent fluid not only breaks through the edge of the swept region to reduce the area of DUR but also significantly develops residual oil which exists in the voids among the preferential flooding channels to reduce the area of HUR the near the injection well as shown in Fig 8(d).

In a word, polymer improves the sweep efficiency by reducing the area of DUR and HUR, which ultimately leads to higher oil recovery. After polymer slugs block the preferential flooding channel in the high and medium-permeability layer, subsequent water is forced into another layers and enhance the oil recovery.

2.5 Conclusions

After polymer slugs weaken the flow capacity of the preferential flooding channel in the high-permeability and medium-permeability layer, subsequent water is forced into the low-permeability layer. At the later stage of subsequent water flooding, the liquid product is mainly contributed by the low-permeability layer, which means that the polymer can adjust the flowing profile in the heterogeneous reservoir.

Polymer not only improves the sweep efficiency by reducing the area of DUR and HUR but also improves the oil washing efficiency by pulling effect on blind-end residual oil, which ultimately leads to higher recovery.

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