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Laboratory evaluations of fiber-based treatment for in-depth profile control

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ABSTRACT

Inspired by the successful implementation in acid fracturing, a fiber-loaded suspension system was designed to investigate inlet injectivity, in-depth mobility and overall plugging effect in unconsolidated high permeability sandpacks. In this paper, a series of experiments were conducted to screen suitable fiber suspension, including additives selection and dynamic plugging tests. Results showed that the formulation of 0.02 wt% citric acid + 0.1 wt% YC regulator + 0.1 wt% sodium tetraborate + 0.12 wt% HPG displayed satisfactory dispersity. Sandpacks equipped with three pressure gauges to detect pressure changes were used for physical experiments. Four parameters (fiber length, fiber concentration, injection rate and permeability) that influenced the plugging efficiency were under discussion. The results revealed that relatively slow injection helped stabilize inlet pressure below upper limit. Three pressures increased in sequence during the subsequent water flooding, indicating that fibers moved forward with permeability reduction in sandpacks. The pressure dropped down but maintained at a high level after the operation finished. By comparison, 0.3 wt% 1000 μm-long fiber injected at the rate of 1 mL/min was found to achieve the best performance under the permeability of 4000–7000mD. And the more serious the heterogeneity was, the more significant the diversion ability of the high permeability layer was. Noticeably, the fluctuations were observed in pressure curves, which was further interpreted by the dynamic plugging mechanism of fiber in four transport processes: "migration-capture-redirection-recapture". With unique slender shape, fibers were flexible enough to bridge and create a compact three-dimensional network structure along the flow direction. Due to high plugging strength and strong penetrability, the new fiber suspension system proves its potential to be an environmentally-friendly candidate in the selection of in-depth diverting agents. The evaluation and mechanism analysis may provide guidance for the operation design of profile control.

1. Introduction

1.1. In-depth profile control

After long-term water flooding and fracturing/acidizing treatment, more oilfields have acknowledged the seriousness of heterogeneity problems (Seright et al., 2003; Zhao et al, 2015a). The water shutoff and profile control technology is an important means to effectively reduce the flow in high permeability channels and increase oil production in water flooding reservoirs (Li et al., 2011; Muggeridge et al., 2014). However, conventional chemical profile control technologies primarily focus on near-wellbore blockage in high permeability streaks, overlooking the sharp decline of plugging efficiency as agents propagate along the flow path. Meanwhile, near-wellbore treatments alone cannot deal with cross-flow between adjacent layers. Eventually, the oil-rich zones deep inside the reservoir remain un-swept, and undesirable water channeling still hinders the reservoir from oil recovery (Burman and Hall, 1987; Liang et al., 2017; Zhao et al., 2018). Moreover, previous heavy-dose gel treatment are becoming increasingly less cost-effective at low oil price time. Both effective and economical placement solutions to reservoir development at high water cut stage have hit a bottleneck.

To better divert water deep inside the high permeability streaks to recover more oil, in-depth displacement is becoming a priority in profile control (Zhao et al., 2015b; Zhou et al., 2017). Currently main attention is paid to chemical agents such as polymer gels, preformed particle gel (PPG), polymer microspheres, and bulk expansion particles (Zaitoun and Chauveteau, 1998; P Zitha et al., 1999; Wang et al., 2001; Ji et al., 2002; Guo and Du, 2004; Fan et al., 2004).

For polymer gels, to prevent poor injectivity in strong gels, weak gels are used constituting low polymer concentration and crosslinker. Although fluidity is better, the plugging efficiency decreases sharply with time (Zhang and Hu, 2014). In addition, adsorption and chromatography of chemical compositions remain to be a problem. In view of unstable crosslinking reactions when using in-situ gels, PPGs are designed as dried mm-sized polymer particles slightly crosslinked at the

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surface. The superabsorbent PPGs are crushed into small particles before injected into a reservoir (Bai et al., 2013). PPGs' feature lies in their ability to swell over 200 times by absorbing aqueous solution. Good deformability makes it conducive to migrate in oil reservoirs. According to Imqam (2015), PPGs have been applied in over 5000 injectors in China. Nevertheless, PPGs are easily broken due to shear by pump, wellbore, and porous media (Yang et al., 2017). Salt-sensitive effect also hinders the actual control of predesigned swelling ratio. PPGs are generally used to plug high permeability cracks and fractures, but they lack enough influence in deep profile control because of large particle size. Polymer microspheres are colloidal dispersion of gel particles dispersed in and swollen by the solvent. Compared to PPGs, the particle size of polymer microspheres s ranges from only 10–1000 nm, therefore they have good propagation properties to seal micro-pore or cracks in low permeability reservoirs (Zaitoun et al., 2007). However, polymer microspheres do not possess as much control over the profile as polymer gels, but their plugging performance on high permeability layers is poor (Qian et al., 2015). Besides, most studies focus on the matching relationship between particle diameter and pore throat size, the interaction between solution and microspheres is not deep enough (Wang et al., 2018).

The new fiber plugging agent we propose belongs to natural cellulose fiber obtained from plants. Its flexible feature helps fibers not only effectively block the high permeability layer, but also migrates deeper in the reservoir. The raw fiber material is cheap and easily accessible, posing no damage to the environment (Movahhedi et al., 2017). In terms of the fiber-based agent, the special resin coat protects fibers from decaying in the short term when profile control operation is implemented, so the plugging performance will not be influenced; on the other hand, fibers are biodegradable due to oxidative and microbial degradation and eventually decompose into carbon dioxide and water (Zhang et al., 2014).

1.2. Fiber used in acid fracturing

In fact, the idea of bringing fibers in profile control was inspired by the success in acid fracturing. Since 1995 when fiber was first employed to prevent the proppant flowback during fracturing operation in South Texas (Zhou and Qi, 2012), fiber-containing fluids has been widely used as fracturing fluids to improve the efficiency of proppant transport during fracturing.

For carbonate reservoirs, the filtration of acid fluids in fractures is severe due to chemical reaction, and acid-etched fractures are short, making it difficult to communicate with remote reservoirs (Li et al., 2016; Liang et al., 2018). The traditional homogeneous polymer system cannot handle and control the leakage at different stages because of serious heterogeneity of the reservoir (J. Ricardo Solares et al., 2008).

While the addition of fibers in fracturing fluid can complete the task of acid transfer in fracturing operations. Fibers do not react with crude oil (Hu, 2015); meanwhile, fibers exhibit good dispersion and suspensibility in fracturing fluids. After adding fibers, the viscosity of fracturing fluid increases significantly, which blocks the fractures at early stages and helps divert acid towards micro-fractures. The fiber improves the suspension properties of proppant, facilitating pre-fracture fluid to carry the proppant transport more smoothly and completely (Xu et al., 2017). It also effectively prevents the rapid gravity separation of proppant in the reservoir, as a result, the proppant distribution in the fracture is more uniform.

Dashti et al. (2009) proposed a combined chemical embolic agent and degradable fiber technology after initial acid fracturing in carbonate reservoirs. It was found that the addition of fibers not only reduced the fluid loss of fracturing fluid, but also ensured the fracture conductivity. Maytham I. Al-Ismail et al. (2008) reported a new type of biodegradable fiber technology in the acid fracturing process of multilayer reservoirs. In Karamay Oilfield, fiber mixed sand was applied in fracturing (Zhang et al., 2013), after fiber fracturing measures were implemented, the average daily oil production increased by 4.4 times. Through the identification and optimization of degradable fibers, Rajesh Sau et al. (2015) believed that the degradable fibers can be fully used for the refracturing of carbonate rocks. He found that advances in fluid diversion technology ensured successful initial stimulation of long-distance (beyond 1000 feet) without mechanical isolation.

1.3. Fiber used in other fields

Fiber is also applied in sand control. Lv et al. (2010) studied fiber-composite sand control technology and used fiber-resin sand mixture to prevent fine silt. After polymer injection, the viscosity of the production fluid rose, the sand production increased, and polymer clogging led to a significant drop in oil production. In view of this, Zhou (2009) proposed a packing method by combining fiber and gravel for sand control. Besides, fibers are regarded as reinforcements in cementing operations. By dispersing in cement slurry to form a network structure, fibers enhance cement strength after consolidation. And fiber cement slurry is also employed to plug wells with serious leakage in fractured limestone (Zhou and Qi, 2012).

1.4. Fiber used in profile control

In terms of water shutoff and profile control, HPAM (partially hydrolyzed polyacrylamide) is the most commonly acknowledged method in oilfields (Arjmand et al., 2012; Wang et al., 2013). Nowadays, large-scale, heavy-dose (> 1000 mg/L) polymer is used with more injection time for profile control. Meanwhile, due to its poor resistance of temperature and salt, damage to the formation, better alternatives are in need (M Barrufet et al., 1998; GC Emesih et al., 1999; L Eoff et al., 2003). Compared with polymer, cellulose fiber ($C_6H_{10}O_5$) has its unique advantages: huge storage capacity in nature, quick regeneration ability (1.0×10^{10}t/a), and nearly pollution-free. From the economic angle, the cost of HPAM reaches 2.3US $/kg while the price of fiber is only 0.24US $/kg. Consequently, as an easily accessible and inexpensive material, fiber is put into investigation for the selection of new substitution under the low oil price age. This article draws inspiration from the successful implementation in acid fracturing and applies it into profile control. However, note that there are some differences between the role fiber plays in acid fracturing and in profile control (Table 1).

In this paper, we introduced a fiber type suitable for in-depth conformance profile control. To prevent fibers from sedimentation during injection, additives were selected to form a suspension system. Then several dynamic plugging tests were performed in sandpacks equipped with pressure sensors. The pressure rose in sequence along the flow direction, proving both plugging ability and migration ability of fibers to move deep forward. From the experiments, fiber length, fiber concentration, injection rate and permeability were recognized as the main factors that influence the final results. Using recorded pressure changes, each performance of profile control was evaluated from three perspectives: inlet injectivity, in-depth mobility and the overall plugging effect. Eventually, we determined the reasonable fiber parameters suitable for field application. Dynamic plugging mechanism and fiber

Table 1
Differences of fiber's function between acid fracturing and profile control.

	Acid fracturing	Profile control
Reservoir type	Carbonate rock	Sandstone/carbonate rock
Blocking target	Large-scale fractures	Fractures/large pores
Fiber parameters	Vary in material, diameter, length, etc.	
Injection parameters	Vary in fiber concentration, injection velocity, PV, etc.	
Injection pressure	High pump pressure	Not too high
Migration ability	To seal the open mouth/ tip of fractures	To ensure stable migration to the deep reservoir