

Degradable fiber and its application in horizontal well acid-fracturing

H W Zhang^{1,3}, X M Yan¹, M Y Cui¹, C Liang¹, J Yan¹, Y P Sun¹, H B Li¹ and S Z Zhang²

¹Research Institute of Petroleum Exploration & Development, Beijing 100083, China

²PetroChina Tarim Oilfield Company, Xinjiang Korla, 841000, China

E-mail: etczhanghw@163.com

Abstract. In order to acidize whole horizontal well interval uniformly, temporary plugging technology was chosen as one of the most effective methods. Laboratory tests were also carried out to evaluate their diverting properties. The results show that clean self-diverting acid could increase its viscosity during reaction with carbonate, and which made it divert to other layers. And for fiber, it has good temporary plugging and degradable performance, which can meet the demand of uniform acidification and lower damage to oil reservoir. According to the analysis of fiber characteristic, some using principles were also given. This technology was applied on ten wells, and temporary plugging and diverting display could be clearly observed by observing pumping pressure change. Furthermore, final production rate after stimulated was increased obviously. All these results showed that this technology could get a better application effect in horizontal well acidification.

1. Introduction

When performing acidification on the carbonate reservoir, the corrosion rate of acid liquid is high on the core no matter the concentrate of the used hydrochloric acid (15% or 20%), for the high content of calcite. Under the same pressure system, the acidification usually effects along high-permeability zone and large pore path, and can hardly works on reservoirs with low permeability and heavy pollution [1]. Especially for horizontal wells of the long well section, the acid rock reaction is fast, the horizontal section is long, anisotropy exists and a lot of wells are completed with open wells and screen tubes, and general acidification fails to evenly form the whole horizontal section [2]. From 1930s, the research and application of diverting acidification and fracture technology has been started domestically, including mechanic diverting, foam diverting, particle temporary plugging and high polymer gel diverting. In most technologies, the special property of diverting agent is used under specified conditions for temporary plugging of high-permeability zone, so the working liquid is forced to divert into the low-permeability zone to increase the reservoir production ratio and well production rate [3-5].

Commonly used methods onsite are liquid chemical diverting and solid particle temporary plugging diverting. The chemical diverting works by increasing viscosity of acid liquid for temporary plugging [6,7]. Besides, adding solid particle into the pumped liquid is a commonly used method, too. Currently, fiber agent is commonly used for the following advantages: good compatibility with formation fluid and rock, no secondary pollution on stratum, good chemical stability in pumping process, good compatibility with the treating fluid, degradable in stratum, no harm to the stratum [8-11].



In this paper, lab experiments on the performance of temporary plugging diverting, degradation and reservoir protection of these two kinds of materials are shown and construction parameters are optimized by combining the experiment results. The onsite results prove the obvious effects of temporary plugging and production increase if achieved.

2. Clean self-diverting acid system

The viscosity of common diverting liquid mainly comes from the gel of polymer, the interaction between polymer molecules of HMW (amount to millions). This acid system usually brings harm to the reservoir and unsatisfying acidification effect. Along with the development of chemical synthesis and application of surfactant, diverting acid technology of viscoelasticity surfactant started to appear.

The viscosity of surfactant comes from the micellar structure generated by gathering of surfactant molecules. After entering the stratum, the acid liquid reacts with the rock and generates CaCl_2 brine. The surfactants interact with the brine and turn into gel aggregate from individual ions, while long spiral micellars are generated. When the solution property changes suddenly, the number of micelle increases obviously and huge layered micelle, gel, is formed. The gel can increase the flow resistance of the acid in the pore path and plug its flowing and force to acid liquid turn to other pore paths with less flow resistance. After acidification, the produced oil gas or mutual solvent contact with long micellars and turn them into spherical micellars, which apparently decreases the viscosity of the residue acid and facilitate the rapid flowback of residue acid and effective clean of the acid-ething paths.

As shown in the process of viscosity increase and gel breaking, the fresh has low viscosity less than 3 mPa.s. However, with the proceeding of the acid-rock reaction, the pH value increases and the viscosity of the residue acid is high and can even reach 1400 mPa.s when $\text{pH}=2.5$, where the pH value keeps increasing but the viscosity remains changes. See figure 1 for the test results.

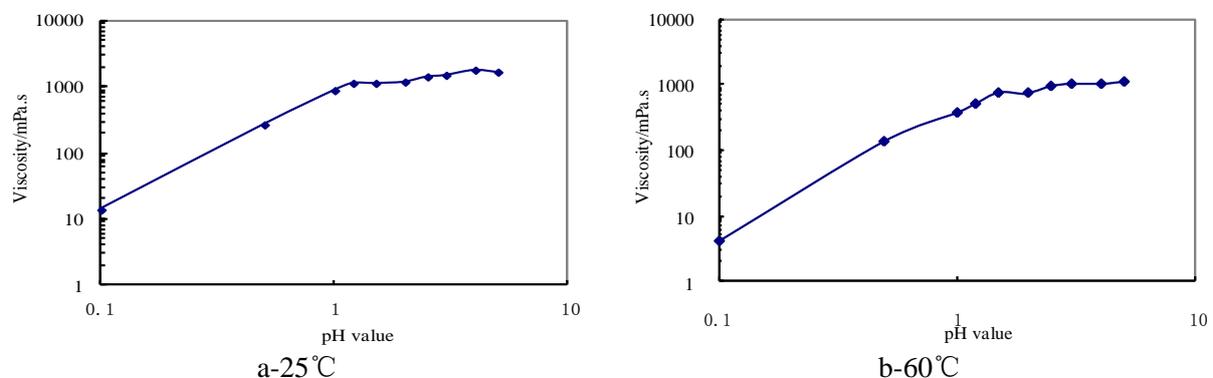


Figure 1. Relationship between viscosity and residual acid concentration under 25°C and 60°C.

To evaluate the diverting performing of the acid liquid, the three-core parallel connection equipment in figure 2 is used as shown in figure 2. The used rock core has a diameter of 2.5 cm and length of 6cm with permeability ratio of adjacent rock cores of 0.5. The test liquid is injected under uniform pressure. Steps for test are: saturating the rock core by brine, measuring the permeability of the rock core (the actually measured permeability are 0.5 md, 1.0 md and 2.0 md), injecting the acid liquid (conventional acid and diverting acid) until the rock core breaks, saturating the rock core by brine again, measuring the permeability of the rock core after acid etching, perform nuclear magnetism scanning on rock core section and observe the wormhole pattern the diverting effect.

As the viscosity of the diversity acid increases after entering the high-permeability rock core, the injecting pressure of acid liquid raises apparently (figure 3), indicating that the diverting acid works well on increasing the flow resistance and diverting the acid liquid.

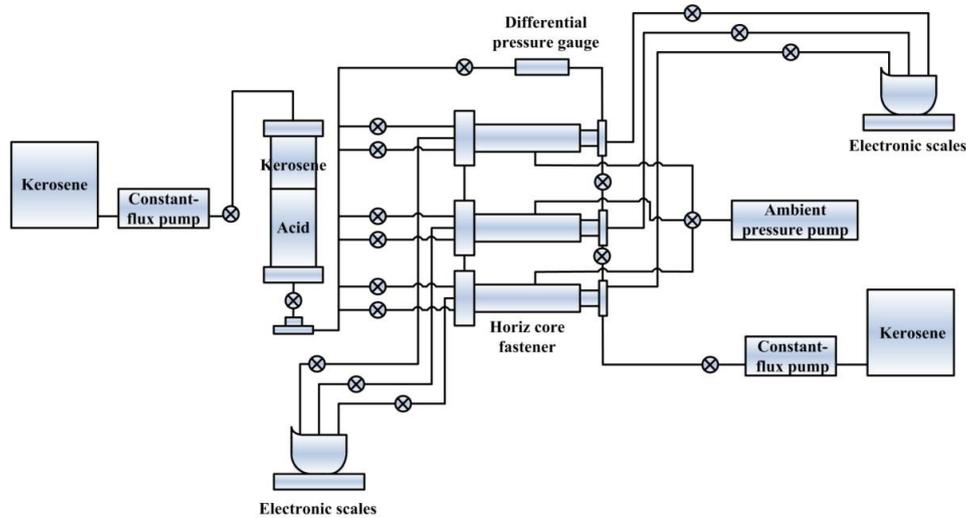


Figure 2. Experimental equipment of self-diverting acid flowing in core.

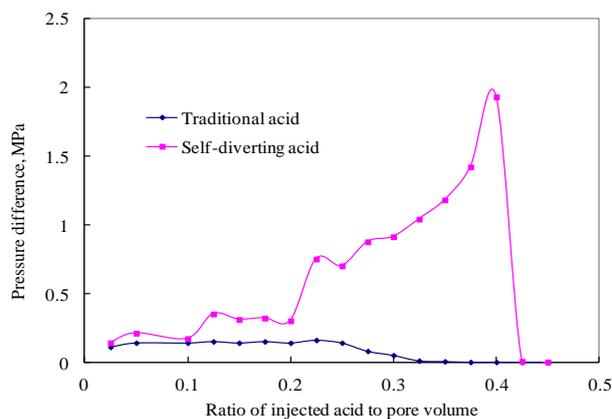


Figure 3. Experimental results of injection pressure with different acid.

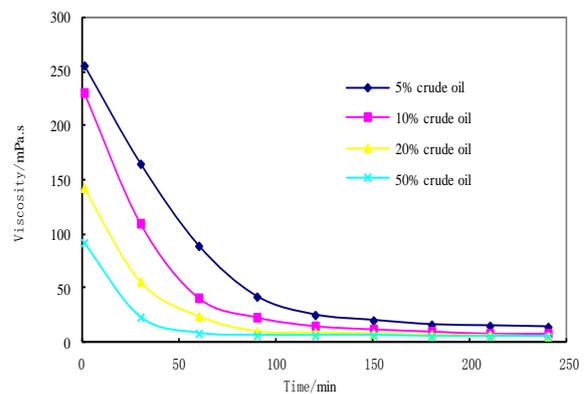


Figure 4. Variation of residual acid viscosity.

By using the cone-plate test system, the relationship between viscosity and time for residue acid after gel broken is measured under the shearing rate of 170 s^{-1} . After acidification, the residue acid gel breaks once it contacts with the oil gas. Add different quantity of light crude into the gel of the diverting residue acid and mix them together (figure 4). As for the gel generated by the cleaning diverting residue acid shall break its structure completely after meeting with the crude but keep its structure when meeting with water except that a large amount of water is used for attenuation and damage its structure and discharge its viscosity, the acid system has a combined function of water controlling.

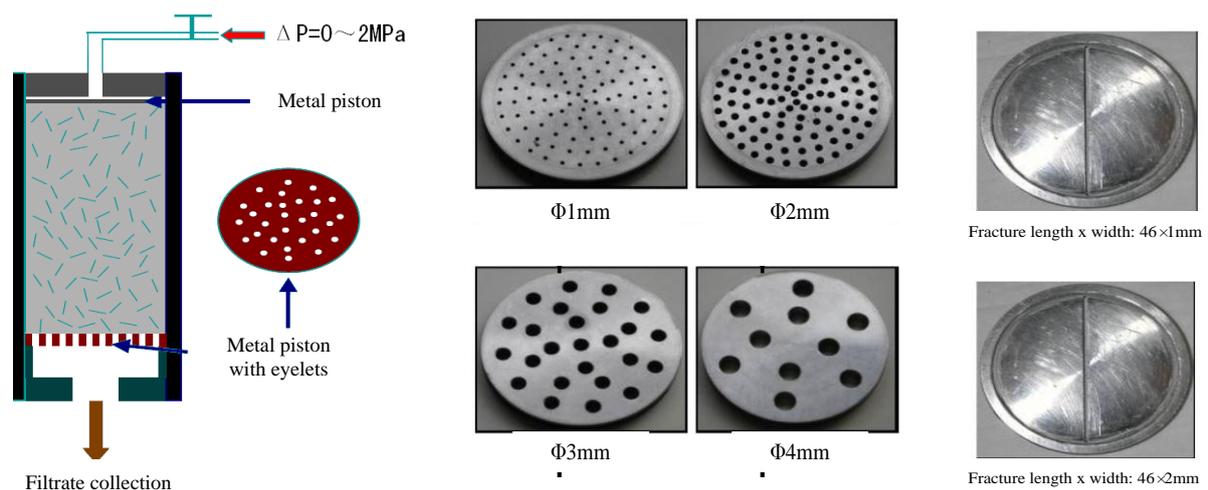
3. Biodegradable fiber

The leak-off control fiber (LCF) is a kind of artificial fiber, which is made of organic polymer by hot melt, drawing, surface coating, chopping and other processes. It is cylindrical with an average length of 4-8 mm and a diameter of 10-20 μm . Table 1 showed its basic properties. This thin material is flexible and can form compact three-dimensional network structure after entering fractures and pores. The action principle is: the fiber itself has the function of bridging into a network and flexible transformation; therefore as the temporary plugging fiber enters an acid-etching fracture or wormhole, a compact "filter screen" takes shape. As a result, the flow resistance of acid liquid is increased, and the purposes of temporary plugging and increasing the diverting efficiency of acid liquid are completed.

Table 1. Leak-off control fiber properties.

Property classification	Test results	
	70°C	90°C
Strength (cN/tex)	4~4.4	6.3~8.8
Extension (%)	12~36	10~28
Elastic Modulus (cN/tex)	22~62	55~114
Flexible degree of recovery (%)	70~85	72~85
Collusion strength (cN/tex)	2.6~4.6	4.4~5.1
Knot strength (cN/tex)	2.1~3.5	4.0~4.6

Disperse the fibers into the water base liquid evenly in onsite construction, and a strong three-dimensional network structure is formed in the dropout zone to control the loss so that the fractures and high-porosity stratum with large dropout can be effectively plugged in the acid fracturing and acidification. Based on different types of fracture width and pores, the temporary plugging system is used for the plugging experiment. See figure 5 for the experiment equipment.

**Figure 5.** API leakage apparatus and different types of metal pistons.

The leakoff volumes in 30 minutes are measured under normal temperature and differential pressures of 0.5 MPa, 1.0 MPa and 2.0 MPa (table 2).

Table 2. Leak off of base fluid and fluid with fiber.

Fracture length × width (mm×mm)	Pressure difference/MPa			
	0.5	0.5	1	2
	Leakoff volume of base fluid (ml)	Leakoff volume of plugging liquid (ml)	of fiber	temporary
46×0.5	25 800	26.5	11.2	4.5
46×1	42 500	46.5	18.8	8.5
46×2	86 500	56.7	24.5	11.4
Φ1mm pore plate	39 800	32.9	15.6	7.3

As shown in the result, fiber has obvious plugging effect and the increase of differential pressure

can also increase the plugging performance of fiber. In analysis, the increase of differential pressure accelerates the formation of temporary plugging layer and reduces further leakoff of liquid. To verify this conclusion, experiments on temporary plugging layer formed under differential pressures of 0.5 MPa, 1.0 MPa and 2.0 MPa were carried out. The experiment result shows that high differential pressure can accelerate the leakoff of temporary plugging liquid and forms compact plugging layers at the opens of fractures and pores rapidly. Therefore, in actual acidification, after injecting of fiber temporary plugging liquid, the construction displacement shall be increased rapidly, so as to make the base liquid leak rapidly and form a compact plugging layer so that the acid liquid is diverted to other stratum.



Figure 6. Fiber dispersion in different kinds of fluid and experimental photos after degradation.

To assess the compatibility and degradation of fiber in different kinds of liquid, five types of liquid are prepared: clean water, temporary plugging liquid, guar gum, clean self-diverting acid and gelled acid with same amounts of fiber added (figure 6). The test result shows, the liquid after degradation are all basically clean, indicating that fiber has good biodegradability. However, the compatibility of fiber is best in clean self-diverting acid and temporary plugging liquid and is second in clean water followed by that in guar gum and gelled acid. As for the guar gum and gelled acid has polymer, there is residue separated out after degradation.

By using residue liquid degraded by the above five kinds of liquid, rock core experiment method is used to assess the permeability damage on rock core by residue liquid degraded by fiber in different liquid mediums so as to verify its performance on stratum protection. The result shows that the recovery rate of permeability of rock core after damaged by residue liquid is 78.32%-95.71%, where the value for clean self-diverting acid is 95.71% as the biggest, indicating that this fiber shows good protective performance after degraded in clean self-diverting acid.

Based on the results, following principles shall be observed in field application: ① add fiber by agitator tanks of the fracturing blender truck; ② mix the fiber with a dosage of 1% to 1.5%; ③ determine the adding speed based on the usage dosage and displacement of fiber-carried fluid; ④ the pumped displacement of subsequent acid liquid shall be larger than twice that of fiber and the fiber-carried liquid; ⑤ multistage injection of fiber-carried liquid and acid liquid can be realized based on the section number of stratum and the degree of heterogeneity, so as to achieve temporary plugging diverting.

4. Field application

Oil field K in Kazakhstan is buried with an average depth of 4335 m and a maximum depth of 6000 m. This oil field has high limestone content and an average calcite content of 75% and bad stratum physical property. As its average porosity is 7.2% and the average permeability is $0.098 \times 10^{-3} \mu\text{m}^2$, the stratum is the type of low porosity and extra-low permeability. With strong heterogeneity, the stratum is divided into high-productive zone and low-productive zone. The micro pore structure contains mainly throat path and natural fractures. The original stratum temperature is 91°C , which belongs to

mesotherm stratum. The formation pressure coefficient of the original stratum is as high as 1.8 to 1.9, which however decreases rapidly, now being lower than 1.0. Horizontal wells and screen tubes are mainly used for horizontal wells of this oil field. The length of horizontal wells is 106 m to 711m and the average horizontal section of 33 horizontal wells is 413 m.

For the rapid reaction between hydrochloric acid and carbonatite and the acid liquid tends to flow in the direction with the least resistance, so general acidification can only changes local spaces close to the horizontal section bottom. For any well with a horizontal section not more than 100 meters, uniform acidification and pollution remove of the whole well section can not be achieved. The test result shows that the diverting acid can works efficiently for rock core with a permeability ratio more than 2. Therefore, for Oil Field K with an average horizontal section length of 413 m and average maximum single-well permeability ration over 100, the temporary plugging diverting technology is an effective solution for uniform transformation.

In 2015, clean self-diverting acid and temporary plugging fiber were used in the guiding experiment on Well A, the first horizontal well. By using screen pipe completion, the average section has a length of 669 m. All together, there were 34 effective sections with an effective thickness of 120 m and a maximum permeability ratio of 160 in the well logging interpretation. Two temporary plugging were proposed to be performed for the horizontal section based on the physical property of stratum. Then the displacement is immediately increased after pumping temporary plugging liquid with fiber is completed based on the lab experiment result, so as to achieve fast leakoff of the base liquid and formation of fiber plugging layer.

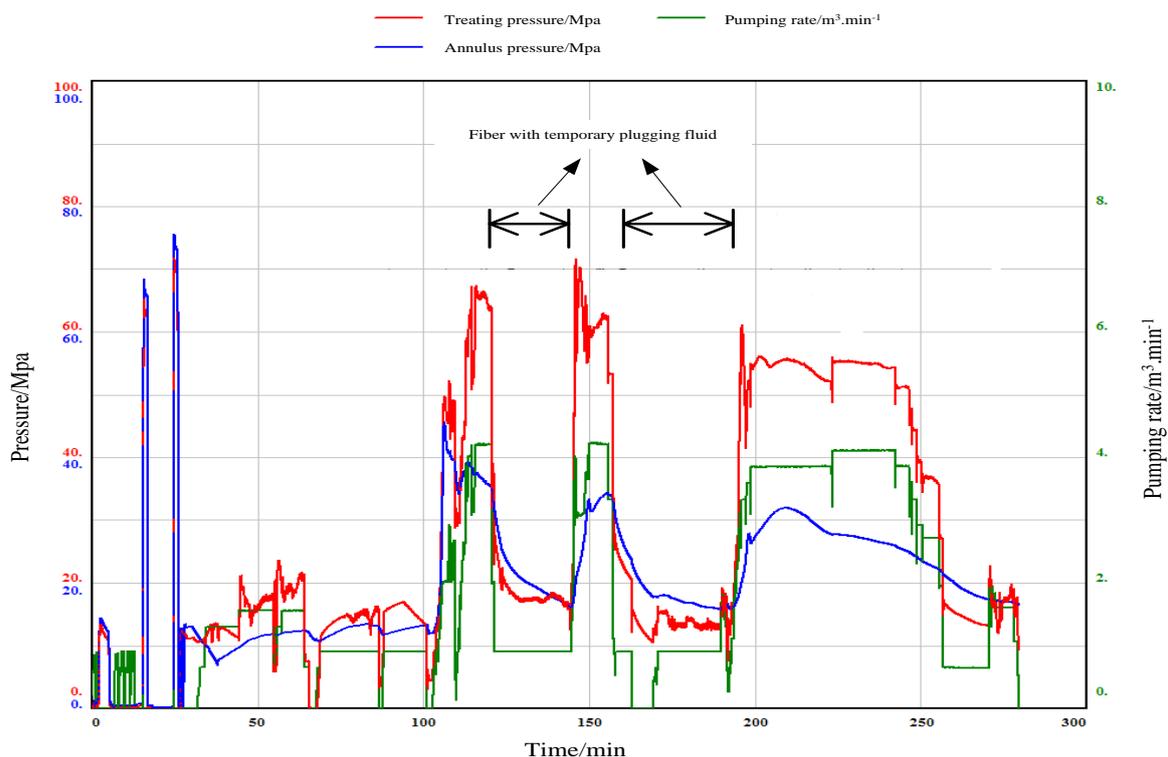


Figure 7. Acid-fracturing curve of Well A temporary plugged by clean self-diverting acid and fiber.

On Oct. 27, 2015, the construction was completed; temporary plugging fiber of 0.68 t was pumped in by a fracturing blender truck twice with a pumped displacement of 0.9 m³/min. After pumping, the displacement was increased to 4 m³/min. See figure 7 for construction curve of temporary plugging acid fracturing of Well A. For the applying of oil casing for connecting and closing the casing valve

and monitoring the pressure change, the well bottom pressure that the casing presented was more accurate. As shown in the construction curve, after the pumped fiber temporary plugging liquid entered into the stratum, the casing pressure kept increasing and dropped after a certain point, indicating that the plugging diverting of liquid and connecting to the new stratum is successful.

After acid fracturing, the well blowing daily output is 183 t/d and cumulative increase of oil is 45 974 t in 300 days with average increasing crude of 153.2 t/d, indicating that good experiment effect is obtained. After the success of horizontal well A, this process is promoted for vertical and horizontal wells of open-hole completion and screen completion. In 2015, the transformation was applied to 6 wells in all with cumulative increasing oil of 23 292 t, average daily increasing oil of single well of 51.64 t/d; in 2016, the transformation was applied to 4 wells in all with cumulative increasing oil of 15 486t, average daily increasing oil of single well of 42.31 t/d, indicating that significant economic benefits were obtained.

Meanwhile, promotional experiments on wells with great physical property difference and uneven production profile and acid-fracturing transformation has become one of the major transformation processes of Oil Field K and related oil fields in Kazakhstan.

5. Conclusions

- By experiment, the clean self-diverting acid is featured in favorable diverting, retardance and low damage, which fit the carbonate reservoir acidification transformation of Oil Field K in Kazakhstan with strong anisotropism and long horizontal well section.
- Degradable fiber can form compact barrier bed, which is an effective method for realizing the intrastratal and interlayer diverting and even transformation. As shown in the experiment result, fibers can reduce the leakoff and form the barrier bed; the greater the displacement is, the greater the pressure difference is, the faster the leakoff of base liquid for temporary plugging fibers, the easier the plugging works and the acid liquid is diverted. Therefore, in actual acid pressure construction, the working displacement shall be increased rapidly once the injection of temporary plugging liquid is injected.

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