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Evaluation and optimization of degradable-fiber-assisted slurry for fracturing thick and tight formation with high stress

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ABSTRACT

Economically producing hydrocarbon from tight formations requires fracturing with a large volume of water and proppants to ensure a highly conductive fracture network. Proppant settling can hinder proppant transportation within fractures, limiting dimensions of the propped fractures and well production rates. This problem is more serious in thick formations that tall fractures are needed. In deep reservoirs with high closure stresses, using high pumping rate or viscous cross-linked gel have their own limitations, while adding degradable fibers can solve the problem. However, no visualized flow experiments have been conducted that can fill the gap between the bench-top measurements and the field tests, thus providing reliable mechanisms to guide the optimization of this technique for a chosen reservoir.

In this study, a systematic screening and evaluation procedure is developed to quantify the effectiveness of degradable fibers on suspending proppants and enhancing fracture conductivity, so as to explore the mechanisms behind this technique. Results indicate that a dilute concentration of fibers in proppant slurry can double proppant placement efficiency without blocking perforation holes on the wellbore; fiber degradation leaves no residue that damages fracture conductivity; fiber degradation does not cause the closure of propped fractures even at high closure stresses.

1. Introduction

To economically produce hydrocarbon from tight formations with low to ultralow permeabilities, hydraulic fracturing is typically used to create a fracture network to enhance hydrocarbon flow, during which a large volume of water with proppants is injected into the formation (King, 2012; Kondash and Vengosh, 2015; Liang et al., 2017b; Wang et al., 2017; Yu et al., 2017). For instance, approximately 51% of oil and 67% of gas is produced from the hydraulically fractured wells in the U.S. in 2015 (EIA, 2016a, 2016b). For gas shale reservoirs, studies have shown that the interference time of two neighboring fractures (i.e., time needed for one hydrocarbon molecule at the center of two neighboring fractures moves to either fracture) is as long as 4–5 years, and this time can be even longer for tight/shale oil reservoirs (Patzek et al., 2013, 2014; Male et al., 2016). Furthermore, extensive observations from various fields also indicate that the larger the volume of water and proppants used per stage/well, the more complex of the hydraulic fractures, and thus the higher of the initial production rate (Cipolla et al., 2009; Mayerhofer et al., 2010; Scanlon et al., 2014; Gallegos et al., 2015; EIA, 2016c).

Proppants are carried by the fracturing fluid and transported into the created fractures to prevent them from closing (Gidley et al., 1990; Palisch et al., 2007; King, 2012). However, they can settle to the bottom of the fracture when moving towards the fracture tip due to gravity. This can lead to the formations of (1) short propped fractures that limit the total stimulated reservoir volume, and/or (2) fractures that are narrow at the top while wide at the bottom (Gidley et al., 1990; Blyton et al., 2015; Shiozawa and McClure, 2016). Because the residual fracturing fluid also sinks at the bottom of fractures and its removal is much slower than the fluid at the top of fractures during flowback, the second shaped fractures are more likely to be affected by liquid-loading that reduces fracture conductivity as well as permeability of the adjacent formation (Agrawal and Sharma, 2013; Sharma and Agrawal, 2013; Sharma and Manchanda, 2015; Liang et al., 2017b, 2017d, 2017c). This problem is more serious in thick formations that tall fractures are needed. Therefore, it is crucial to reduce proppant-settling velocity and improve the proppant placement

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efficiency, thus enhancing the fracture conductivity.

To reduce proppant-settling velocity, two typical methods applied in the field are increasing pumping rate by using slickwater and increasing fracturing fluid viscosity by using cross-linked gel (Montgomery, 2013; Al-Muntasheri, 2014; Barati and Liang, 2014). For deep reservoirs with high stresses, using a high pumping rate with the current slickwater does not normally perform as well as expected, while using cross-linked gel needs a high concentration which can cause serious formation damage due to the undegraded residues (Wang et al., 2008; Vincent, 2009; Xu et al., 2011; Barati and Liang, 2014; Gu and Mohanty, 2015; Weaver et al., 2015). Therefore, new technique is needed for harsh environments.

Fibers have been used in sand control (Heitmann et al., 2002; Zhou et al., 2004; Lawal et al., 2015; Shi et al., 2015) and preventing proppant flowback (Howard et al., 1995; Romero and Feraud, 1996; Ramones et al., 2014; Sallis et al., 2014), while degradable fibers have been used in temporary blocking for refracturing deep reservoirs with high temperatures that mechanical blocking or plugging does not work reliably (Xue et al., 2015; Wang et al., 2015, 2016). Degradable fibers can also be used in slurry to prevent proppants from settling during hydraulic fracturing, then degrading with little residues (Bulova et al., 2006; Bustos et al., 2007; Sitdikov et al., 2009; Kayumov et al., 2013). Recently, a similar technique called "channel fracturing" is developed and tested in multiple fields by Schlumberger (Sukovatiy et al., 2015; Letichevskiy et al., 2017). However, among these studies, only results from small-scale bench-top experiments and field-scale tests were provided; no visualized flow experiments were conducted that can fill the gap between two scales and thus provide reliable mechanisms behind this technique. Secondly, using a mixture of fibers and proppants in the fracturing fluid has a potential risk of blocking the perforated holes on the wellbore, and this problem has not been discussed or examined in the relevant studies published so far. Thirdly, it is missing a systematic screening and evaluation procedure that can ensure a good performance of fibers on suspending proppants for fracturing a chosen reservoir.

In this study, a series of laboratory evaluations are designed to quantify the effectiveness of degradable fibers on suspending proppants and enhancing fracture conductivity, so as to explore the mechanisms behind for optimizing their properties for a chosen reservoir. Key properties include degradation rate of fibers, static and dynamic proppant placement efficiencies, ability to flow through a perforated hole, impact of fiber degradation on the propped fracture under a reservoir condition (including temperature, pressure and closure stress), and impact of potential fiber residues on fracture conductivity. A systematic screening and evaluation procedure is thus established that combines bench-top experiments, large-scale slot-flow experiments, and field pilot tests.

1.1. Target reservoir

The field pilot tests are conducted in a tight-sandstone gas reservoir that locates in the western Tarim Basin in Xinjiang Province in China. At a depth of about 3000–3600 m, this reservoir is characteristic of high stress (i.e., around 45 MPa), normal reservoir pressure (i.e., around 33 MPa), and normal reservoir temperature (i.e., 60–65 °C). Well logging and core analysis results indicate that the reservoir rock has a porosity ranged from 0.83% to 10.8% with an average of 5.5%, and a permeability ranged from 0.08 mD to 1.90 mD with an average of 0.79 mD. Two neighboring vertical wells are used in this pilot test, and hydraulic fracturing is conducted with the cross-linked guar for creating long and tall fractures that maximize the gas production rate. Details on fracturing fluid, proppant, degradable fiber, and fracturing design in the pilot tests refer to later sections.

2. Materials

2.1. Fracturing fluid

The fracturing fluid used for stimulating this tight-sandstone gas reservoir contains approximately 0.12 wt% hydroxypropyl guar, 0.15 wt% cross-linker, 0.1 wt% cross-linking regulator (i.e., alkali), 1 wt% temperature stabilizing agent (i.e., antioxidant), 1 wt% flowback surfactant, 0.1 wt% bactericide, and traces of other additives. In all laboratory tests of this study, the identical formulation as used in the field is applied to prepare the mimicked fracturing fluid for evaluating the degradable fibers. Its viscosity is approximately 90 mPa·s at a shear rate of 100 s^{-1} at 20 °C.

2.2. Proppant

Since this reservoir has a high horizontal stress (i.e., closure pressure) that is above 45 MPa, 20/40 ceramic proppants are chosen to prevent hydraulic fractures from being closed. The roundness and sphericity of the chosen type of proppants are both higher than 0.8 according to ISO 13503-2, 2006. Its crushing rate is less than 5 wt% at a stress of 52 MPa, and its bulk density is 1.58 kg/m^3. In all laboratory tests of this study, the proppant slurry has 240 kg/m^3 proppants in the mimicked fracturing fluid, which is similar to the one used in the field pilot test.

2.3. Degradable fiber

The similar type of degradable fiber as used for temporarily-plugging-and-diverting fracturing (Zhou et al., 2004; Wang et al., 2015, 2016) is chosen to reduce the proppant-settling rate in this study. This fiber is a copolymer of lactic acid with glycolic acid. Depending on the synthesis time, its molecular weight can be tuned, which in turn changes the degradation time and degradation temperature of the fiber. Since the reservoir temperature is 60–65 °C, 60°C-degradable fibers are synthesized and applied in both laboratory tests and field pilot tests of this study. They have an average length of 6 mm and an average diameter of 10–13 μm.

3. Evaluation methods

3.1. Fiber degradation test

To evaluate the degradation rate of the fibers, multiple beakers are prepared, each containing 200 mL DI water and 2 g dispersed 60°C-degradable fibers (i.e., 10 kg/m^3 fibers). After all beakers are sealed with plastic films and transferred into a 60°C-water-bath, the fibers are kept being stirred by magnetic stir bars. At different predetermined time-points (e.g., 1 h, 1.5 h, 2 h, etc.), one beaker is taken out; the undegraded fibers in this beaker are screened out by a 150-mesh sieve, whose dry weight is measured beforehand (w_1). Then, this sieve and the screened fibers on it are completely dried at 40 °C for measuring the total weight (w_2). The degradation ratio at this time-point is defined by Eq. (1) as follows.

$$\left(1 - \frac{w_2 - w_1}{2\ g}\right) \times 100\% \quad (1)$$

For one set of degradation test, the degradation ratio is measured at 8 different time-points from 1 h up to 12 h; then, the whole set is repeated twice to obtain the average degradation ratio at each time-point (24 measurements in total).

3.2. Static proppant-settling test

Proppant-settling test is applied to evaluate the performance of the fracturing fluid on suspending and/or carrying proppants with and without the degradable fibers. In this study, the static proppant-settling tests are conducted in 100-mL graduated cylinders, where the proppants fall by gravity in the mimicked fracturing fluid at the no-flow condition. In the comparative tests, the proppant slurries are well mixed with and without 2.4 kg/m^3 degradable fibers (i.e., a fiber-to-