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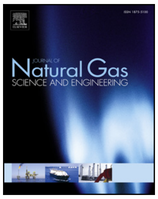

Expandable proppants to moderate production drop in hydraulically fractured wells

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ABSTRACT

Hydraulic fracturing is recognized as the primary technique to achieve economic oil and gas production from low permeability reservoirs like shale and tight-sand formations. One of the main challenges facing the oil and gas industry is maintaining the proppant functionality in the subsurface to guarantee a sustainable production rate and higher ultimate recovery. Proppant crushing and proppant embedment may diminish production from stimulated wells especially when bottomhole pressure is reaching low flowing pressures in soft and deep formations like Haynesville or Tuscaloosa Marine Shales. Experimental measurements and field observations have shown the strong impact of proppant stress and proppant embedment on reducing fracture conductivity. In this work, we introduce a novel material developed in order to achieve higher fracture conductivities at a minimum cost. The new type of proppants, so called "Expandable Proppants" (**EP**), is able to remotely control the expanding force and maintain the functionality of placed proppants. The presented proppants are made out of thermoset shape memory polymers which are activated by formation's in situ temperature to effectively maintain or even increase fracture's width. A fully coupled numerical model is developed to study the effectiveness of expandable proppants and evaluate fracture conductivity enhancement for different combinations and distributions of **EP**. In addition, a series of experiments were conducted in a modified **API** conductivity cell to verify the increase in fracture conductivity. Numerical and experimental results demonstrate that proppant expansion can increase the permeability up to 100%. Different conditions of confining stress and proppant sizes are studied to verify the optimum proppant design. This product can extend the lifetime of the fracture and ensure lasting production.

1. Introduction

Hydraulic fracturing treatments have become considerably popular in the last two decades and contributed to most of the inland production increase in the United States. Over two million wells have been stimulated using this technology until 2013 according to US Department of Energy reports. Low permeability reservoirs that were not economically viable in the past become all of a sudden attractive and productive resources thanks to this technique. To keep the induced fractures open, proppants are used to prop fractures and maintain fracture hydraulic conductivity. Fracture conductivity is considered the most important factor for post fracturing performance and overall effectiveness of stimulation jobs.

In terms of economic perspectives, the combination of hydraulic fracturing and horizontal drilling technologies has enabled the production of oil and gas from tight sand and shale formations, as known as unconventional reservoirs. Shale gas has emerged as a major new energy source in North America in the past decade. In 2000, shale gas contributed only one percent to the U.S. natural gas production; this number grew to over 20 percent by 2010. Similar gains are being observed in Canada, and promising shale gas resources are being investigated now in China and Argentina. The market pain point in recovering oil and gas from shale plays is the fast and sudden drop in production due to post-treatment fracture closure. As a matter of fact, in some soft shale plays, hydrocarbon production in fractured wells show no difference from non-fractured wells after a year of production. Among different shale plays in North America, the most distinguishable ones with proppant related issues are Haynesville shale, Eagleford shale, Woodford shale and Tuscaloosa Marine Shale, which are roughly contributing to 42% of current natural gas produced in the United States nowadays. It is notable that the global market size of the proppants is currently about 9 billion dollars while there is no solution in the market to address the issues like fracture's closure that can be solved by the proposed expandable proppant.

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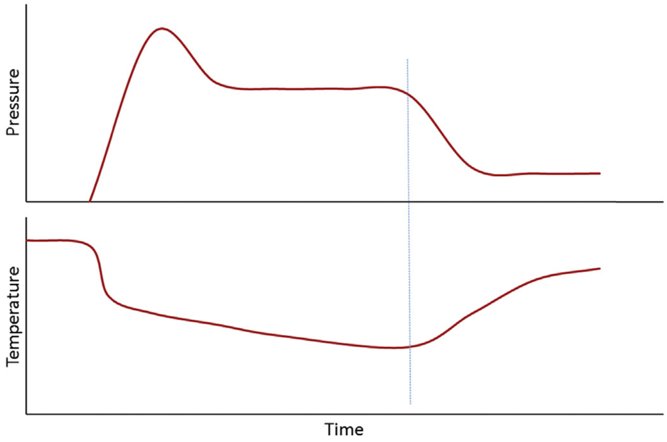

Fig. 1. Bottomhole net pressure and temperature history during a typical hydraulic fracturing job. Vertical line marks the end of pumping and, consequent increase in temperature can be used as the triggering temperature for the expandable proppant.

Although sand has been the most common proppant due to its low cost and availability, sand grains may embed into the formation or collapse and generate fines when subjected to large enough compressive stresses during production and depletion. There exist few solutions to enhance sand properties using ceramic coating or just utilizing ceramic particles to achieve superior performance. The proppants can also be treated with surface modification agents (SMA). SMA is formulated using liquid resin to consolidate the proppant pack. In addition, resins increase the consolidation of the proppant pack to prevent proppant production (Dusterhoft et al., 2004). A 10%–30% increase in conductivity is observed in laboratory experiments using the SMA-treated proppants (Dewprashad et al., 1999). Such treatments need to be planned carefully because the resins can be very sensitive to pressure and temperature. Our proposed resin-based expandable proppant (EP) is introduced as a disruptive product to widen induced hydraulic fractures in order to prevent sudden reduction in production. This EP is made of Shape Memory Polymers (SMP).

The developed smart EP would respond to in-situ temperature after placement inside the formation for a long enough time without any need to an external trigging source. Fig. 1 shows a typical response of the bottomhole pressure and temperature during and after a typical fracture job. Fluid and proppants have been pumped for a period of time. The termination of the pumping period is marked by a vertical line and followed by an extended period of shut-in that lasts usually much longer than the pumping time. Of particular interest here is that the temperature of fracturing fluid and surrounding rock decreases until shut-in time. The following increase in temperature can be used for activation of smart proppants.

The proposed technology may reduce the need for refracturing due to fracture closure or proppant embedment in soft formations and overpressurized deep formations. Proppant flow-back may occur in very low-permeability formations; the expanded proppants may also prevent other proppants from flowing back into the well. In other words, once the smart proppants are activated they may act as barriers for the sand flowback to the wellbore.

The proposed proppant should not only sustain the high reservoir temperature without showing large plastic deformations, but should also release their stored strain slightly below the reservoir temperature. Therefore, our option is limited to thermoset polymers, not thermoplastic polymers. Thermoset polymers are established by chemical crosslinks introduced during fabrication, thus they do not soften or melt like thermoplastic polymers (Hiemenz and Lodge, 2007). Hence, they are more appropriate for downhole applications due to higher rigidity and stiffness in high temperatures. It is notable that the released stress should be large enough to open the crack but not too large to crush the formation rock, thus we are looking for stress release ranging from 10 to 30 MPa, which is a reachable range with stiff shape memory polymers.

Proppant transport is an important factor for the success of a hydraulic fracturing treatment. The slightly lower density of the proposed proppant in comparison to sand ensures better placement of proppants due to slower settlement rate. Numerical simulations of hydraulic fracturing treatments in naturally fractured reservoirs have shown that fracture opening at the intersection of fractures is prone to larger amount of compressional stress in comparison to the rest of the fracture (Dahi Taleghani and Olson, 2014; Dahi Taleghani, 2010). This strong compressional stresses at the intersection (branching) point may reduce fracture conductivity at these points, hence branching points may act as bottleneck during the production life of the wellbore (Asala et al., 2016). Therefore, expandable proppants placed at these specific places may help to remove the bottlenecks induced at the intersection points similar to the way that coronary stents work.

In the next section, a brief description of the thermomechanical properties of Shape Memory Polymers (SMP) is presented, as well as its programming method. Then, the experimental setup to examine SMP's function as proppant and its impact on the fracture conductivity is introduced. Following, a coupled numerical model is presenting for simulating proppant bed in-situ expansion inside the hydraulic fracture and changes in its petrophysical properties. The numerical model is further validated by comparison with widely used Carman-Kozeny relationship which was originally driven for sand particles without cementing between the grains.

2. Shape memory polymers

Shape memory polymers (SMPs) are a type of polymeric materials which are capable of storing a prescribed shape indefinitely and recover the original shape by specific external trigger, e.g. heat, electrical current or pH. When heated to a glass transition temperature (T_g), thermoset polymers goes from a rigid plastic state to a rubber elastic state. There are several classes of smart materials with the shape memory effect, along with shape memory ceramics and shape memory alloys, but SMPs have the advantage of being cheap, easier to process, nontoxic, biodegradable and can achieve much higher degrees of deformation relaxation rather than stress release (Li, 2014). Such characteristics made them ideal for many applications, including medical devices, sports clothing, temperature sensors, connectors and shrinkable tubes. SMP foam has also been used as a sand management alternative for gravel packing. The screen can shrink up to 70% of its original size when in place to prevent sand production (Carrejo et al., 2011). SMP particles are also utilized as an expansive cement additive (Dahi Taleghani et al., 2016) and expandable LCM (Mansour et al., 2017) to seal cement voids and microannulus cracks. In this paper, we show an application of stiffer SMPs to widen the gaps within the fractures rather than sealing them (Fig. 2).

SMP particles memorizes their initial shape, but they need to be programmed to first change into a temporary shape and then transform back into the original shape upon exposure to triggering conditions. A typical programming method is a four-step thermomechanical cycle, involving changes in temperature (T), stress (σ) and strain (ε). The process, shown in Fig. 3, starts at temperatures above T_g, applying a high strain deformation (pre-deformation, or pre-strain). Then it is followed by the maintaining the applied strain while cooling down the material below T_g. The third step is the removal of the stress in the glassy state by reheating the SMP to its initial temperature without applying constraint, the pre-strain returns back to zero (unconstrained recovery) and the particle recovers the initial shape (activation). This process is known as free shape recovery (step 4). After the activation the entropy will reduce (negative entropy change).

The EP original shape is spherical. Considering the fact that we only need expansion of proppants in the direction perpendicular to fracture