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Experimental and theoretical study of fracture conductivity with heterogeneous proppant placement

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A B S T R A C T

Proppant distribution patterns play a significant role in the improvement of stimulated well performance. Multiple studies indicate that an uneven proppant distribution within fractures can considerably reduce well productivity. However, fluid flow is not necessarily restricted by a non-uniform proppant distribution. A novel technique called channel fracturing greatly increases fracture conductivity by creating open channels inside fractures that are caused by heterogeneous proppant placement. In this study, an effective experimental model was established to measure the flow capacity with heterogeneous proppant placement. A series of experiments on a discontinuous proppant distribution and conductivity was conducted by considering the formation temperature. The fracture conductivities of a heterogeneous proppant placement and uniform proppant distribution were compared. The effects of the fibre concentration, proppant properties, rock properties, proppant mass placement patterns, and fluid damage on the fracture conductivity and proppant embedment were also investigated to quantify the key factors affecting the effectiveness effectivity of the propped fracture. In addition, new analytical models were derived to calculate the proppant embedment and fracture conductivity with a discontinuous proppant distribution. The creeping deformation model was adopted to predict the changes in the proppant embedment and fracture conductivity over time. This study contributes to the optimization of channel fracturing treatments and elucidates the effect of a heterogeneous proppant placement on fracture conductivity.

1. Introduction

The purpose of hydraulic fracturing is to generate a conductive proppant pack for improving the flow of reservoir fluid to a wellbore. Proppants, such as coated sand and ceramics, are mixed with fracturing fluids and then injected into the generated fractures to resist closure stress, hold fractures open, and reach the critical fracture conductivity for fluids to flow. The overall stimulation performance is greatly affected by diminishing both the fracture aperture and fracture conductivity under an uneven proppant distribution (Cipolla et al., 2009; Warpinski, 2010; Warpinski et al., 2009; Yu et al., 2015). Many scholars have conducted field data analysis, experimental studies, and computational modelling of the transportation and distribution of proppants (Alotaibi and Miskimins, 2015; Guo et al., 2014; Sahai et al., 2014). Fluid flow is not necessarily restricted by a non-uniform proppant distribution.

Channel fracturing is a novel hydraulic fracturing technique that promotes heterogeneous proppant placement and creates a network of highly conductive channels; this technique relies on the intermittent pumping of fibre-laden and proppant-laden fluids at a high frequency (Ahmed et al., 2011; Ajayi et al., 2011; Gillard et al., 2010; Inyang et al., 2014; Tinsley and Williams Jr, 1975). Pillars and void spaces can be generated and cause proppants to be lodged at these irregularities when the fracture conductivity is increased, as shown in Fig. 1 (Palisch et al. (2010). Such flow patterns greatly increase the deliverability of hydraulic fractures, improve fluid clean-up and hydrocarbon recovery, and consequently enhance well performance (Ajayi et al., 2011). Channel fracturing has been increasingly applied in tight and low-permeability oil/gas formations, such as shale gas, CBM (Coal Bed Methane), and unconsolidated sandstone reservoirs (Ejofodomi et al., 2014; Kayumov et al., 2014; Medvedev et al., 2013; Yudin et al., 2014). Well productivity consistently increases after channel fracturing. Rhine et al. (2011) studied non-normalized data from samples of fifty wells and found that channel fracturing increased hydrocarbon production by

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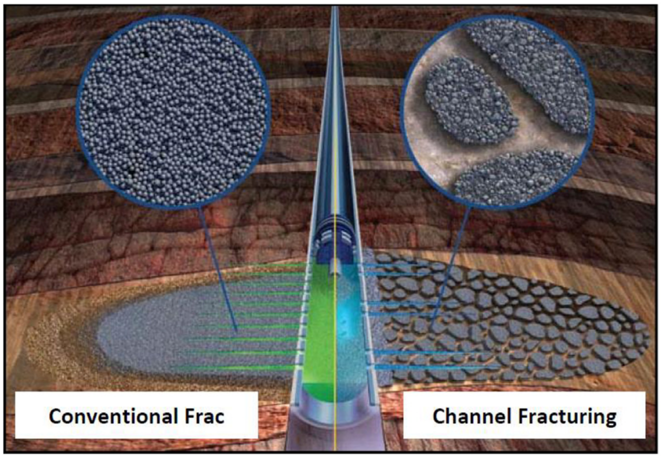

Fig. 1. Comparison of channel fracturing and conventional fracturing (Gillard et al. 2010).

32%–68%. Yudin et al. (2012) found that oil production at the wells in the Taylakovskoe oil field increased by 44% on average after 10 channel fracturing treatments. Kayumov et al. (2014) demonstrated that oil production was nearly two-fold higher in wells stimulated by channel fracturing than in offset wells stimulated by conventional fracturing. These field cases demonstrated that the discontinuous proppant distribution in channel fracturing improves well productivity. High fracture conductivity plays the most significant role in improving well performance in channel fracturing. Thus, studying the effect of a discontinuous proppant distribution on channel fracture conductivity is highly important.

Several analytical models can be used to calculate fracture conductivity under a discontinuous proppant distribution. Gillard et al. (2010) established an analytical model based on the Navier–Stokes equation to calculate the effective permeability of an open-channel fracture and verified their results with experiments. Yan et al. (2015) applied the Darcy–Brinkman equation to model the fluid flow in propped fractures and upscaled this equation to evaluate the equivalent permeability of fractures by using the homogenization theory and finite element numerical simulation. Several sensitivity factors of flow conductivity, such as the shape, distribution, and size of clusters, were analysed. Zhang and Hou (2016) derived analytical models to calculate the influence of the proppant embedment and SMA material on the channel fracture conductivity. The creeping deformation model was adopted to predict the proppant embedment and fracture conductivity. However, the theoretical models contain many assumptions, and the analytical models do not consider the real fracture geometry, proppant settling, uneven proppant distribution, and effect of fracturing fluid damage.

Experimental studies were conducted on fracture conductivity with a discontinuous proppant distribution. Gillard et al. (2010) placed some proppant pillars in a conductivity cell to simulate heterogeneous proppant placement and tested the fracture conductivity over the closure pressure. However, their work only generated three experimental data points and did not clearly analyse the influencing factors of the fracture conductivity with a heterogeneous proppant placement. Medvedev et al. (2013) found that effective system permeability is a function of the closure pressure and that the conductivity in channel fracturing is several orders of magnitude higher than that in conventional fracturing. Qu et al. (2015) investigated the effects of the proppant diameter, proppant slug number, and fibre concentration on the channel fracture conductivity. The key factors affecting the flow conductivity were analysed through orthogonal experimental design and grey relational analysis. Although many experimental tests were conducted in their work, the maximum fracture conductivity was calculated to be 1200 $\mu m^2 \cdot cm$, which might not be an accurate quantitative characterization of conductivity with a heterogeneous proppant placement. Gillard et al. (2010) and Medvedev et al. (2013) obtained a maximum fracture conductivity that was up to 1.5–2.5 orders of magnitude higher than that obtained by Qu et al. (2015). However, systematic experimental research that elucidates the mechanisms underlying discontinuous propped fracture conductivity and quantifies the key factors affecting fracture conductivity with a heterogeneous proppant placement using shale and unconsolidated sandstone samples is still lacking.

In this work, an effective experimental model was established to measure the fracture conductivity with a heterogeneous proppant placement, in which an open channel was propped. A series of experiments on the discontinuous proppant distribution and conductivity was conducted by considering the formation temperature. Five uncertain factors, namely, the concentration of fibre, proppant properties, rock properties, proppant mass placement, and fluid damage, were also investigated to quantify the key factors affecting the effectivity of the propped fracture. In addition, new analytical models were derived to compute the proppant embedment, proppant deformation, and fracture conductivity. The results of this study provide insights into the effect of heterogeneous proppant placement on fracture conductivity.

2. Experimental apparatus and methods

2.1. Experimental equipment

The experimental apparatus, including a constant-flux pump, an automated hydraulic intensifier system, a modified API conductivity cell, three pressure gauges, and a PC data acquisition system, was used to test the fracture conductivity (Fig. 2). This setup simulates real reservoir conditions. However, the flow rate provided was restricted, and a constant-flux pump with a 1000 ml/min flow rate limitation was configured. The hydraulic load frame can apply up to 120 MPa of closure pressure under a formation temperature of 150 °C. All experimental operations were based on modified API standard recommended practices (Nguyen et al., 2005a, 2005b; RP 61, 1989).

2.2. Specimen preparation

Lujiaping shale samples, unconsolidated sandstone samples, and a steel plate were cut into dimensions that match the hastelloy conductivity cell, as shown in Fig. 3. The samples were designed to have dimensions of a 177 mm length, 38 mm width, and 15 mm thickness to accommodate the cell dimensions. The prepared samples were only 15 mm in thickness because of the thickness limitation of the hastelloy conductivity cell. The samples were coated by a high-temp RTV silicone gasket to ensure that the fluid only flowed through the propped fractures. Three types of proppants, namely, resin coated sand, ceramic proppant, and quartz sand, were prepared with the same proppant concentration and proppant size to investigate the effect of the proppant type on fracture conductivity with a heterogeneous proppant placement. A nano-composite fibre was developed to prompt the proppant to gather into a mass; this fibre was studied in previous works (Ahmed et al., 2011; Gillard et al., 2010; Xiao et al., 2013). KCl brines (2 wt%) were used as the testing fluid to flow from the intermediate container to the propped fracture to measure the conductivity.