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Productivity enhancement by stimulation of natural fractures around a hydraulic fracture using micro-sized proppant placement

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ABSTRACT

Hydraulic fracturing in naturally fractured rocks interconnects a natural fracture network to the wellbore. Improving the connectivity between a hydraulically created fracture and the pre-existing natural fractures can significantly improve the hydraulic fracturing efficiency. In this study, a well stimulation method is proposed to enhance the conductivity of fracture system around the hydraulic fracture. This stimulation technique involves placing micro-sized proppant particles in the natural fracture system around the hydraulic fracture at the leak-off pressure condition in order to maintain the fracture systems' conductivity during the post-fracturing production.

The equations for one-dimensional suspension flow around and perpendicular to the hydraulic fracture, accounting for rock deformation and particle capture, have been derived. The effects of permeability reduction due to particle straining are incorporated in the analytical model. The laboratory tests on the solid-particle suspension injection into the natural fractures of a coal core at elevated pressures are successfully matched by the model. The experimental results confirm there is an optimum concentration of placed particles whereby a maximum permeability is retained; this optimal proppant particle placement yields nearly a three-fold increase in permeability. The analytical model has been tuned from these experiments to calculate the optimum concentration of placed particles and predict the productivity improvement after stimulation of the fracture system around the hydraulic fracture.

A case study is presented to demonstrate the productivity enhancement by applying the proposed technique in a coal-bed-methane (CBM) reservoir. The laboratory-based analytical model predicts a six-fold increase in the productivity index. Examples for the possible practical applications of the developed technology in hydraulic fracturing or stimulation treatments in coals are also presented.

1. Introduction

Coalbed methane (CBM) reservoirs can demonstrate a variety of permeability values with a high degree of variability in stress sensitivity depending on their cleat and fracture network (fracture systems). Based on the stress sensitivity, these reservoirs provide a logical basis to experimentally investigate the potential stimulation strategies to reduce sensitivity or increase stimulation effectiveness. Worldwide, a large portion of CBM resources remain unrecovered in low-permeability reservoirs as a result of low productivity indices. In order to achieve economical production rates, most coal seam gas wells require some form of stimulation (Palmer, 2010; Sayyafzadeh et al., 2015).

Hydraulic fracturing is the most often used stimulation method for CBM reservoirs and is designed to interconnect the fracture systems to the wellbore (Holditch et al., 1988; Xu et al., 2013a,b). However, hydraulic fracturing in coals can create complex fractures within a complex system of joints, natural fractures and cleats (Jeffrey et al., 1992, 1995, 1998; Jeffrey and Settari, 1998; Johnson et al., 2002; Palmer et al., 1993). These cases not only illustrate the differences between hydraulic fracturing in CBM and clastic reservoirs, but also highlight the varying interactions that can occur in coal between a natural fracture system and a hydraulically created fracture. Highly-instrumented, large-scale, hydraulic fracturing experiments in coals indicate that a large portion of the

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stimulated reservoir volume (SRV) is unlikely to be accepting the range of proppant typically used in a hydraulic fracturing treatment to maintain conductivity (Flottman et al., 2013; Johnson et al., 2010a,b; Scott et al., 2010). Therefore, any process that can enhance post-frac conductivity by stimulating the complex and pressure dependent fracture systems around the created hydraulic fractures could significantly improve the efficiency of hydraulic fracturing and enlarge the SRV for CBM and other naturally fractured reservoirs.

A method called graded proppant injection has been proposed for stimulation of natural fracture system in coals below the fracture initiation pressure (Khanna et al., 2013; Keshavarz et al., 2014, 2015a,b). The purpose of injecting micro-sized graded proppant particles into the natural fracture systems is to keep them open during the production stage. As the pore pressure declines during the injection along the tortuous flow path from the wellbore to the reservoir, the natural-fracture apertures also decrease. The particles are injected in order of their size increase which provides the uniform filling of the open fractures by the particles.

In the present study, the graded proppant injection method is applied in fractured wells, i.e. above the fracturing pressures. Extending the process from simply reducing near-wellbore stress to aiding hydraulic fracturing in fracture systems requires the injection of the micro-sized proppant particles of a very fine mesh, within the initially injected fluids, followed by larger proppant particles. Small particles leak-off into natural fractures, keeping them open during the production. Ideally one would design the particle injection schedule to create a partial monolayer of micro-sized proppant placement in the natural fractures, keeping them open during the following water and gas production. It may yield a great expansion of the stimulation reservoir volume if compared with that created by the hydraulic fracturing process. Consequently, it may ultimately increase the well productivity (Fig. 1).

An additional benefit of the micro-sized proppant particle placement in natural fractures is a decrease in the fluid loss due to leak-off during the hydraulic fracturing, thereby benefitting the stimulation treatment by extending the fracture half-length.

In the present work, the laboratory study and mathematical modelling for stimulation of natural fracture systems around a hydraulically created fracture are carried out. The respective core flow experiments at pressures representative of both over pressure injection as well as decreased pressure drawdown phases are performed. The core flooding tests performed by injecting suspended particles into the natural fracture systems of a coal core. By evaluating different particle sizes at varying concentrations of placed particles, an optimum concentration of particles is found whereby maximum permeability values are achieved. The analytical model for one-dimensional suspension injection perpendicular to the hydraulic-fracture face is derived. The model matches the above experiments, and the model coefficients are tuned. This laboratory-based model predicts the productivity improvement of fracture systems around a hydraulically created fracture by the placement of differing sized proppant particles during fracture fluid leak-off.

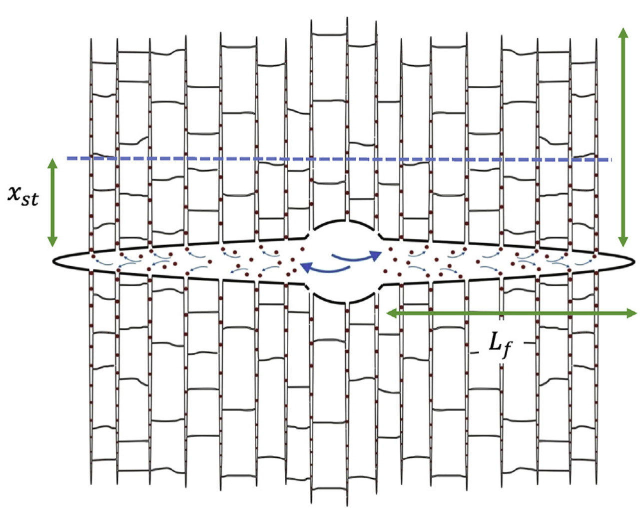

Fig. 1. Schematic of micro-sized graded proppant placement in the fracture systems surrounding the main hydraulically created fracture.

The structure of the text is as follows. Section 2 presents the laboratory materials, experimental set up and the experimental results. Section 3 describes a laboratory-based mathematical model for the stimulation of fracture systems intersecting the main hydraulic fracture. Section 4 discusses the prospective for the graded-proppant injection application in different CBM reservoirs. Sections 5 and 6 present discussions of the results and conclusions of the work.

2. Experimental study

2.1. Materials and experimental set-up

Three core samples C_1-C_3 were cut from a bituminous coal block from the Affinity coal mine, West Virginia, US. The bituminous coal block and core sample C1 are shown in Fig. 2.

Core sample C_1 is used for the proppant injection tests. Core samples C_2 and C_3 are used in uniaxial stress tests for measuring their geomechanical properties. The radius (r_c), length (L_c), Young's modulus (E) and Poisson's ratio (ν) for all three core samples are presented in Table 1. The values of Poisson's ratio and Young's modulus are determined for samples C_2 and C_3 and averaged to estimate them for sample C_1.

The selected proppant particles for the proppant placement tests are micro-sized, hollow, borosilicate glass, microspheres SPHERICEL 110P8 and SPHERICEL 60P18 (Potters Industries LLC, South Yorkshire, UK), with the particle sizes of $r_p = 5$ μm and $r_p = 9.5$ μm, respectively.

All flooding tests, before and after proppant injection, are conducted by a custom-built coreflooding apparatus designed to simulate the particles' placement at fracturing leak-off conditions. This coreholder system is connected to a data acquisition system, which allows the monitoring and control of the inlet and back pressures as well as the inlet flow rate of suspension. A stainless steel high-pressure vessel is connected to the system for injecting the suspensions of the micro-sized particles into the core sample. Effluent samples are collected and analyzed using a particle counter. A schematic view of the setup is illustrated in Fig. 3.

Before starting the flooding tests, the core samples are tightly wrapped with a Teflon tape to prevent any water leakage between the core sample and the rubber sleeve. All tests are conducted at constant ambient temperature of 25 °C. The core sample C_1 is fixed in the core holder and consolidated with a few load cycles to remove hysteresis and ensure the results are reproducible. Initial cleat permeability, k, and cleat porosity, $\varnothing_f$, of core sample C_1 are measured according to Gash's method (Gash, 1991) and the values are 5.8 mD and 0.54%, respectively. Once the initial cleat permeability, k, and cleat porosity, $\varnothing_f$, of a core sample are measured, the average fracture aperture, h, and fracture spacing, a, are related to the porosity and permeability of the cleat network by assuming a regular fracture and cleat arrangement. For matchstick arrangement of matrix blocks, the formulae for cleat porosity and permeability are as follows (Reiss, 1980; Seidle, 2011):