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Model development of proppant transport through hydraulic fracture network and parametric study

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ABSTRACT

A model capable of simulating proppant transport through hydraulic fracture network is developed and summarized in this paper. The proppant transport model (PTM) is able to capture multiple proppant transport patterns, including suspension, saltation and creeping. These patterns are first identified, and then quantified to establish proppant transport equations. The governing equations are programed into a three-dimensional, finite-difference model to simulate the proppant transport process. The PTM is coupled to a previously developed hydraulic fracture network propagation model, which updates essential input parameters such as fracture geometry, velocity distribution and pressure profile for each step. In every step, the proppant transport model extracts values for these parameters and solves the mass transport equations for all three patterns. Finally, the PTM generates proppant concentration, fracture conductivity and distribution throughout the created fracture network and predicts, at the end of the designed treatment the propped stimulated reservoir volume (PSRV) – a critical indicator of long-term stimulation effectiveness for hydraulically fractured oil/gas reservoirs. Parametric Studies of several important treatment, operational, reservoir, and geomechanical parameters are done in this paper to illustrate the impact of each factor on the PSRV.

1. Introduction

Hydraulic fracturing is one of the most effective and efficient methods to enhance oil and gas recovery from unconventional reservoirs. Pre-existing natural fractures are commonly present in the unconventional reservoirs. Due to this distinct character, hydraulic fracturing treatment generates a hydraulic fracture network instead of a bi-wing planar fracture in the formation. Proppant transport behavior in the hydraulic fracture network system is more complicated and is not able to be simulated using conventional methods. The complexity of the fracture network causes the evaluation of the effectiveness of the treatment very difficult.

Traditionally, engineers use the concept of stimulated reservoir volume (SRV) to evaluate the effectiveness of the hydraulic fracturing treatment. The quantification of the SRV is often estimated by micro-seismic mapping. However, the micro-seismic is not capable of indicting the actual propped-open portion of the fracture network, which actually contributes to oil and gas recovery. Ahn et al. (2014) firstly stated the concept of the propped-open stimulated reservoir volume (PSRV) that represents the actual propped-open portion of the created fracture network. The PSRV is the actual effectively stimulated volume, which is contributing to oil and gas recovery. Weng et al. (2011) developed a model able to simulate the interaction between the hydraulic fracture and pre-existing fracture network. The proppant transport function in this model is not described and simplified. Mack et al. (2014) conducted proppant transport experiments in a set of intersecting transparent narrow slots to mimic the scenario of hydraulic fracture network. The experiment described some observation and phenomenon of proppant transport behavior in the narrow slot network. Recently, more researches investigating particle transport in hydraulic fractures are conducted. Blyton et al. (2015) proposed a CFD-DEM type method to model particle transport in hydraulic fractures. The integrated model is able to capture detailed effects of particle – particle, particle – fracture interactions. The research suggests that the propped open length by proppants could be shorter than expected due to low proppant velocity because of concentration effect. Shiozawa et al. (2016) compared simulation results from Pseudo-3D and fully 3D models. The result indicates that the P3D results are consistent with the fully 3D results and with better efficiency. The research also investigates the effect of tip screen out and fracture closure. The results suggest that tip screen out is not significant in shale reservoirs, but the settling of proppants are phenomenal and is detrimental to proppant

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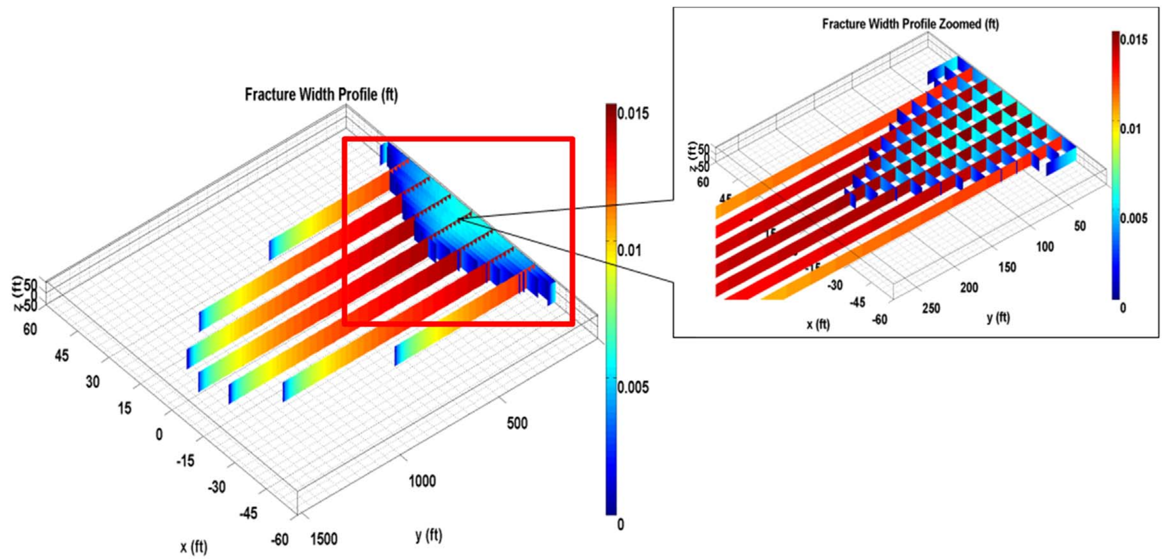

Fig. 1. Hydraulic fracture network geometry at the end of 60-min treatment (Ahn et al., 2014).

placement. Han et al. (2016) investigated proppant transport in complex fracture geometry also using CFD method. The authors established several simplified scenarios for intersecting fractures such as T-junction and crossing geometries to mimic a part of the natural fracture network. The results indicate that a great portion of proppants remain in the major fracture instead of entering the natural fractures. The research also indicates that lighter proppants, higher fluid viscosity, and higher pumping rate increase the amount of proppants entering into the natural fractures and vertical propped coverage.

Most of the works focused on proppant transport in a bi-wing planar fracture, which is not suitable for naturally-fractured unconventional reservoirs. The previous experiments or numerical studies are done under fixed fracture geometry, which neglects the effect of changing fracture geometry and fluid flow velocity. Some of the previous researches use CFD-DEM method to model particle movements in the fractures. The computational burden makes it really difficult to simulate proppant transport in a larger scale and efficient application. The physics governing proppant transport in fracture network is not identified and quantified either. Also, there is no published model with multiple governing physics that simulates proppant transport in a hydraulic fracture network dynamically.

From our previous research, Chang et al. (2016) summarized and also developed the governing physics of proppant transport through hydraulic fracture network. The author provided quantification of each governing physics such as advection, turbulent dispersion, settling, bedload transport, and the uneven fraction proppant mass flux at fracture intersection. All the major governing physics were identified and quantified. In this paper, we developed a three-dimensional, finite-difference, and multi-mechanistic proppant transport model to quantify the proppant distribution and concentration in the hydraulic fracture network in naturally fractured unconventional reservoirs. This is the first model that includes comprehensive governing physics of proppant transport in naturally fractured system. With the model, one is able to quantify the actual propped-open stimulated reservoir volume (PSRV) and evaluate the effectiveness of the treatment.

2. Model development

2.1. Hydraulic Fracture Propagation Model (HFPM)

In order to model proppant distribution in complex hydraulic fracture network, multiple physics needed to be captured. Two models are coupled to capture the physics – (1) Hydraulic Fracture Propagation Model, and (2) Proppant Transport Model. The Hydraulic Fracture Propagation Model is coupled to the Proppant Transport Model to capture the proppant placement during the injection period. The Hydraulic Fracture Propagation Model developed by Ahn et al. (2014) is a finite-difference based model with capability to simulate fracture propagation in a naturally-fractured shale gas reservoir. This model captures the interaction between hydraulic and natural fractures, fluid flow in matrix and geo-mechanics of the rock. Complex fracture propagation can be generated as a function of different input parameters. The HFPM assumes two sets of uniformly spaced, orthogonal pre-existing natural fractures in the reservoir. The procedure starts with the injection of fluid into the perforation with corresponding pressure increase. Using an iterative method, fluid flow equation and geo-mechanical equation are solved at the same time. Once the pressure exceeds the initiation criterion of fracture propagation, the grid block then is converted into a fracture block. If the treatment continues, fracture propagates through the pre-existing fracture; if the fracture encounters an intersection, crossing and lateral initiation criteria are calculated to govern the propagation. Depending on different input parameters, the fracture either propagates across the intersection without opening secondary fractures, initiates opening of the secondary fracture, or both. Thus, for a designed treatment schedule and other scenario parameter input assumptions, the HFPM generates a hydraulic fracture network in the reservoir. Fig. 1 illustrates results from a case in which the HFPM treated at 17 bbl/min rate, with fluid viscosity of 2 cp, a total volume of 42,840 gallon is injected for half of the simulated cluster. The treatment information is provided in the appendix section.

The proppant transport models developed in this article captures fluid flow velocity, fracture geometry and other essential input parameters throughout the fracture network domain that are output from the HFPM as in each time step, and uses that as input in simulation of particle transport dynamics.

2.2. Mechanisms of proppant transport and the proppant transport model (PTM)

Proppant transport in slick water is a complex process that is controlled by multiple physical phenomena and proceeds occurs under different flow regimes simultaneously, as described in an article by Chang et al. (2016, In preparation). Four regions can be identified that are associated with proppant transport in the fracture. The first zone near the tip of the propagating fracture is the pad solution that